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THE APPLICATION OF REMOTE SENSING TO THE DEVELOPMENT
AND FORMULATION OF HYDROLOGIC PLANNING MODELS

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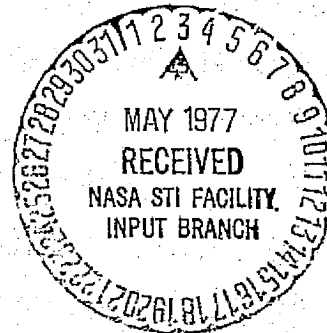
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TABLE OF CONTENTS

	<u>PAGE</u>
I. INTRODUCTION	1
II. SUMMARY OF RESULTS AND CONCLUSIONS	3
III. REVIEW OF PREVIOUS PHASES	5
3.1 Investigation of Driver Phenomena	6
3.2 Development and Validation of Remote Sensing Model	9
3.3 Identification of the Efficiency of Remote Sensing in Determining Parameters of Hydrologic Models	10
IV. APPROACH TO THE PRESENT EFFORT	13
V. PROCEDURES FOR EXTRACTION OF HYDROLOGIC DATA FROM LANDSAT IMAGERY	16
5.1 Importance of Surface Cover to Hydrologic Models	19
5.2 Alternative Techniques for Analysis of LANDSAT Imagery	22
5.3 Visual Extraction of Hydrologic Land Use from LANDSAT Imagery	24
5.3.1 Land Use Information Content of the Four LANDSAT Bands	24
5.3.2 Use of Composite Imagery	27
5.4 Recommended Procedure for the Visual Analysis of LANDSAT Composite Imagery	29
5.4.1 Preparation of "Tuned" Diazo Composites	32
5.4.2 Image Projection	36
5.4.3 Watershed Delineation/Ground Truth Overlay	37
5.4.4 Analysis of Ground Truth	37
5.4.5 Classification of LANDSAT Themes	40
5.4.6 Quantification of Hydrologic Parameters	42
VI. DEVELOPMENT OF REMOTE SENSING AND APPLICATION TO TEST WATERSHED	47

	<u>PAGE</u>
6.1 Model Development	47
6.2 Application of the Model to Test Watersheds	50
6.2.1 Data Collection and Reduction	53
6.2.2 Peak Event Modeling of Bucklodge Branch	61
6.3 Implications of the Introduction of Remote Sensing Data into Hydrologic Planning Model	70
VII. TECHNOLOGY TRANSFER TO THE USER COMMUNITY	71
7.1 Description of the User Community	71
7.2 Impediments to Expanded Use of Remote Sensing in Hydrology and Suggestions for Overcoming Them	73
7.3 Summary of User Contacts Made to Date	74
APPENDIX A	77
APPENDIX B	84
BIBLIOGRAPHY	

LIST OF FIGURES

	<u>PAGE</u>
FIGURE 1: Flow Chart of Current Phase	14
FIGURE 2: Sensitivity of Runoff Peak to Surface Complex	17
FIGURE 3: Sensitivity of Runoff Peak to Seasonal Changes	18
FIGURE 4: Surface Cover Variables of Watershed Models	20
FIGURE 5: Reflectance Characteristics of MSS Bands	26
FIGURE 6: Diazo Transparency	30
FIGURE 7: Contact Print of Diazo Composite	31
FIGURE 8: Tuned Diazo Image - Urban Areas	34
FIGURE 9: Seasonal Changes in Forest Signature	35
FIGURE 10: ECOSYSTEMS' Image Analysis Device	38
FIGURE 11: Separation of Land Use Themes	41
FIGURE 12: Classification of Land Use Themes	43
FIGURE 13: Division of a Watershed into Hydrologically Homogeneous Sub-Areas	45
FIGURE 14: Assignment of Hydrologic Parameters	46
FIGURE 15: Strip Hydrograph Model Components	49
FIGURE 16: Overland Flow Module Output	51
FIGURE 17: Bucklodge Branch Watershed	55
FIGURE 18: S.C.S. Soil Survey Engineering Data	56
FIGURE 19: LANDSAT Diazo Composite, Bucklodge Branch, October 1973	58
FIGURE 20: LANDSAT vs. Aerial Inventory Error - Bucklodge Branch	62
FIGURE 21: Bucklodge Branch - Major Subbasins	63
FIGURE 22: Bucklodge Branch - Unit Strips	64
FIGURE 23: Hydrologic Schematic - Bucklodge Branch	66
FIGURE 24: Gage Records - Event of 15-17 June 1976	68
FIGURE 25: Modelled vs. Observed Discharge, Event of 15-17 June 1976	69

LIST OF TABLES

	<u>PAGE</u>
TABLE 1: Summary Descriptions of Hydrologic Processes	7
TABLE 2: Potentially Important Drivers as Related to Hydrologic Processes	8
TABLE 3: Surface Cover Classification Results, Muddy Branch Basin	12
TABLE 4: Radiometric Properties of the MSS Bands	28
TABLE 5: Strip Hydrograph Model Inputs	50
TABLE 6: Classification Results - Bucklodge Branch Watershed	60
TABLE 7: Model Parameters - Bucklodge Branch	67

I. INTRODUCTION

The launch of LANDSAT has for the first time provided the water resource manager and practical hydrologist with broad prospects for efficient acquisition of essentially real-time data. These are usable for hydrologic land use assessment, surface water inventory, and for the extraction of information pertinent to soil properties. This information has value not only by and in itself, but also to construct the watershed transfer function for hydrologic planning models aimed at estimating peak outflow from rainfall inputs.

The reduction of satellite data to practical, operational information requires a clear, easily applicable methodology for converting these data into quantitative hydrologic parameters.

The fundamental objective of this effort is the development of such a methodology and its transfer to hydrologic users. It was realized that such technology transfer could be made far more effective by the parallel development and eventual demonstration of the results of a model, specifically structured to take full advantage of the capability of LANDSAT - for example, its frequent recurrence and consequent ability to determine seasonal variations in the watershed's conditions. The category of planning models was chosen for development and demonstration because of its great practical importance in the design of waterworks, because of the wide diffusion of such models down to capillary levels within the hierarchy of water resources users, and because their implementation is relatively simpler than management models, thus making optimum use of the resources available for this effort.

Consequently, the effort was structured along two major routes: the development of a hydrologic planning model specifically based upon remotely sensed inputs, including its test and verification from existing records; and the application of LANDSAT data to supplying the model's quantitative parameters and coefficients. Included was the investigation of the use of LANDSAT data as information inputs to all categories of hydrologic models requiring quantitative surface parameters for their effective functioning.

The effort thus far has consisted of three phases. The first focused on the definition of the "drivers" - those hydrologic processes to which peak runoff is most sensitive - and upon the synthesis of a simple yet effective model for the estimation of long-recurrence outflows. The results of the first phase effort were presented in the Final Report, "The Application of Remote Sensing to the Development and Formulation of Hydrologic Planning Models," dated January, 1975. The second phase extended this work to include the development of a routing model for use in sensitivity analyses, and a quantitative investigation of the accuracy and completeness of the hydrologic information which can be extracted from remotely-sensed imagery.

These findings were reported in the January, 1976, final report. The current phase has concentrated on validation of the model and upon the synthesis of a simple methodology for performing hydrologic analyses from LANDSAT imagery.

II. SUMMARY OF RESULTS AND CONCLUSIONS

The objectives of the current effort have been to complete and test a hydrologic planning model making maximum use of remotely-sensed inputs; to document procedures for extraction of pertinent parameters from satellite data; and to expose the model and techniques to prospective users.

In the course of this investigation, several findings and conclusions have been reached and are described below:

The Importance of Surface Parameters to Hydrologic Models

The surface-related parameters used by existing hydrologic models (Manning's "n," S.C.S. Curve Number, etc.) can be derived from LANDSAT imagery to the required accuracy. The opportunity is available to take advantage of the radiometric and multi-temporal properties of the data to facilitate identification and classification. Moreover, potentials exist for remote monitoring of soil and soil moisture which would be of great value to hydrologists.

Planning Model Development

A simple model which is amenable to remote sensing inputs has been developed and tested; it exploits LANDSAT data for surface cover input and can accept soil moisture information as this becomes possible. The test was performed for the Bucklodge Branch, Maryland, watershed. Accuracy achieved to date appears commensurate with those of conventional models. The principal purpose envisioned for the model and benchmark test is to demonstrate to prospective users that satisfactory results can be achieved and to show how similar analysis procedures might be applied to their watershed with their models.

Synthesis of Analytic Procedures

Our experience has shown that a significant share of hydrologic modeling is being performed under the auspices of local governments. Consequently, two impediments to the use of satellite data arise. First, there is a lack of standard procedures for extraction of hydrologic data. Second, the expense involved with current computer/optical practices is a deterrent to use. This report proposes a procedure for simple visual analysis of LANDSAT images which is accurate enough for use in conjunction with hydrologic models. It has been determined further that these techniques extend beyond the field of hydrology and can have equal applicability to agriculture, land use, etc., analyses.

Contacts with Prospective Users

To date, contacts have been made with both foreign and domestic users. Due to the relatively new state of modeling overseas, the response has been greater there. One Italian region has embarked on the analysis of a major watershed, spawned in part by this investigation. Other regions have expressed interest. Domestic acceptance will be fostered by the demonstration of concise procedures and satisfactory results. Such a purpose is intended for this document.

III. REVIEW OF PREVIOUS PHASES

Of critical concern to water resources planners and engineers is the ability to forecast peak flow events. The capacity to estimate the magnitude and duration of large-recurrence outflows has a significant impact upon the accuracy of sizing and designing waterworks, and thus on their cost.

The tool available to the planner for these purposes is the hydrologic model. Although the inputs of different models vary, all require significant quantities of physiographic and hydrologic information; these data are typically expensive to obtain and are often only partially available. Remote sensing offers a new source of information which formerly had to be acquired by less efficient means or ignored altogether.

The first phases of this effort conducted from February, 1974 to December, 1975, addressed four pertinent topics:

- 1) Identification of the "drivers" of peak flow events, i.e., the hydrologic phenomena (infiltration, antecedent soil moisture, etc.) to which the watershed's outflow is most sensitive.
- 2) The development of a model compatible to the maximum degree with remotely-sensed hydrologic inputs.
- 3) Preliminary verification of the model for actual watersheds.
- 4) Initial identification of the efficiency of remote sensing in determining the parameters of the model.

3.1 Investigation of Driver Phenomena

The purpose of this investigation was to achieve a valid statistical comparison of the rates and magnitudes of the hydrologic processes contributing to the runoff from long-recurrence events. This was accomplished over a significant sample of watersheds, with wide variation of climatology, terrain, and physiography. The comparison allowed the determination of which are important and which can be neglected without significant loss of accuracy.

Rain falling on a watershed is subject to several processes which abstract water and govern the flow. Those which produce the most significant changes to flow rates and volumes "drive" the basin outflow. Table 1 describes the hydrologic processes; Table 2 presents the "drivers" of each. It shows that several processes can be omitted in the formulation of a peak rate model because of their limited impact. For example, the rates corresponding to interflow, percolation, and evapotranspiration are very slow in comparison with other processes such as rainfall, infiltration and overland flow. Also, interception and depression storage become saturated early in large rainfall events and therefore are inconsequential to peak event modelling.

Therefore, except for very special circumstances, peak flow can be adequately modelled by considering only precipitation, infiltration and surface flow - both overland and in the channels. The means by which this can be accomplished will be discussed in Section V.

TABLE 1

SUMMARY DESCRIPTIONS OF HYDROLOGIC PROCESSES

<u>HYDROLOGIC PROCESS</u>	<u>DESCRIPTION</u>
Interception	Moisture caught and stored on plant leaves and stems or other impermeable objects; eventually evaporated back into the atmosphere.
Infiltration	Downward movement of water from the surface into the soil.
A) Interflow	Lateral subsurface water movement toward stream channels.
B) Percolation	Downward movement of water through soil to groundwater (area where pores of soil or rock are filled with water).
C) Base Runoff	Water from interflow and percolation which moves underground to the channel.
Evapotranspiration	Upward movement of water in gaseous state from the surface.
A) Evaporation	
B) Transpiration	Movement of water through plants to the atmosphere.
Precipitation Excess	Retention of excess rainfall in surface depressions.
A) Depression Storage	
B) Surface Flow	
C) Channel Flow	Flow of water in natural channels.
Total Runoff	Sum of runoff from underground processes (base runoff) and overland flow (direct runoff).

TABLE 2

POTENTIALLY IMPORTANT DRIVERS AS RELATED TO HYDROLOGIC PROCESSES

<u>HYDROLOGIC PROCESS</u>	<u>PRINCIPAL DRIVERS</u>	<u>SECONDARY DRIVERS</u>
Overland Flow	Slope Roughness of Soil & Cover Drainage Density & Pattern	--
Infiltration	Soil Permeability Antecedent Soil Moisture Soil Moisture Capacity	Vegetative Cover Slope Water Turbidity Temperature
A) Interflow	Soil Permeability Subsurface Moisture Gradient Flow Length, Slope	--
B) Percolation	Soil Permeability Subsurface Moisture Gradient Soil Depth	--
Evapotranspiration		
A) Evaporation	Temperature Antecedent Soil Moisture Soil Permeability	Water Turbidity Wind
B) Transpiration	Temperature Solar Radiation Vegetative Cover Antecedent Soil Moisture	Wind
Depression Storage & Detention	Depression Density Cover Retention	Slope
Interception	Duration of Rainfall Intensity of Rainfall Cover Composition, Age, Density	Evaporation Rate

3.2 Development and Validation of Remote Sensing Model

The following criteria were followed in the structuring of a peak-rate model:

- 1) The model would be modular, to allow the user flexibility of application,
- 2) The model would maximize potential input from remote sensing.

During the first phase a model of the Rational Formula type was developed. It is of the form:

$$Q = 2Ll \xi \left[\frac{\phi (l) (n)^{.6}}{\xi^{.4} s^{.3} (3600)} \right]^{\frac{1}{0.4 - \frac{1}{\alpha_3}}} \quad (1)$$

where:

Q = maximum outflow rate, $m^3/sec/km^2$

L = channel length, m

l = length of average strip, m

n = average Manning's "n"

ϕ = routing factor

$\xi = K \alpha_1 T^{\alpha_2}$

K = infiltration and spatial correction factor

T = rain recurrence interval, years

s = average slope, m/m

$\alpha_1, \alpha_2, \alpha_3$ = constants, function of location

The output of this model is the expected peak discharge rate for a watershed for a rainfall of T years recurrence interval (A complete derivation is contained in the January, 1975 report). This model was

verified against records of 31 experimental watersheds of the Agricultural Research Service. The results showed this model to equal or better the performance of other formulations of the Rational type.

In the second phase, the two criteria of modularity and remote sensing input maximization were applied to the development of a more comprehensive model capable of routing water overland and through the channels. This model as envisioned would have maximal utility for un-gaged, predominantly rural watersheds, i.e., those where remote sensing could play a significant role. Completion and verification of the model occurred during the current effort and will be reported later in this document.

3.3 Identification of the Efficiency of Remote Sensing in Determining Parameters of Hydrologic Models

This task was comprised of hydrologic land use analysis of watersheds located as given below:

- 1) Chickasha, Oklahoma
- 2) Oxford, Mississippi
- 3) Blacksburg, Virginia
- 4) Muddy Branch, Maryland

The findings of this analysis are summarized in the following:

- 1) Substantial hydrologic information can be measured from LANDSAT imagery. The parameters identified and measured were: surface water bodies, surface cover classes, channel lengths, and watershed area. Both single-band and color composite imagery were examined; the latter offered much more information and greatly facilitated analysis.

- 2) Of particular value were seasonal LANDSAT observations. For example, the October imagery showed the watersheds when vegetation density was low; this made the higher-order streams visible. More channels could be measured from the Chickasha, Oklahoma, image than appeared on the U.S.G.S. topographic map at the same scale. LANDSAT imagery clearly shows that effective drainage density varies cyclically throughout the year.
- 3) It became apparent that published records do not reflect current surface cover conditions, since the watershed's land use typically alters with time. The October, 1973, LANDSAT imagery demonstrated that surface cover for the Chickasha Basin had changed from that described in the latest published data (1967).
- 4) The Oxford and Blackshurg watersheds were used to evaluate the discriminability of stream courses, forest cover, surface water and impermeable areas from LANDSAT images. The relative value of each of the four MSS bands was assessed; Band 7 was found most useful for surface water, while Band 5 offered more detail in vegetated areas. It was concluded, though, that composite imagery optimized the contributions of all bands.
- 5) A complete hydrologic land use analysis was performed using color composite imagery for the Muddy Branch basin in Montgomery County, Maryland. The accuracy of the process was verified by comparison with aerial photography ground truth. The results are summarized in Table 3. Overall error was about 6%, acceptable for computation of surface cover factors of hydrologic models.

TABLE 3

SURFACE COVER CLASSIFICATION RESULTS, MUDDY BRANCH BASIN

	<u>AREA</u> <u>LANDSAT</u>	<u>% OF</u> <u>WATERSHED</u>	<u>AREA</u> <u>AERIAL</u>	<u>% OF</u> <u>WATERSHED</u>	<u>INVENTORY</u> <u>ERROR</u>
Urban	557 ha	11	649 ha	12	-14%
Forest	1,242 ha	24	1,292 ha	23	- 4%
Lakes	30 ha	1	29 ha	1	+ 3%
Soil	575 ha	11	547 ha	10	+ 5%
Fields	2,852 ha	54	3,028 ha	55	+ 6%

IV. APPROACH TO THE PRESENT EFFORT

The current phase of this effort brought the prior work to a conclusion through four tasks:

- Task 1 The complete development of the routing model.
- Task 2 The derivation of hydrologic parameters from LANDSAT imagery for an additional watershed, making a total of five for which such analysis has been performed.
- Task 3 The documentation of procedures for extracting hydrologic information from LANDSAT imagery.
- Task 4 Demonstration of the procedures and model to a selected group of users.

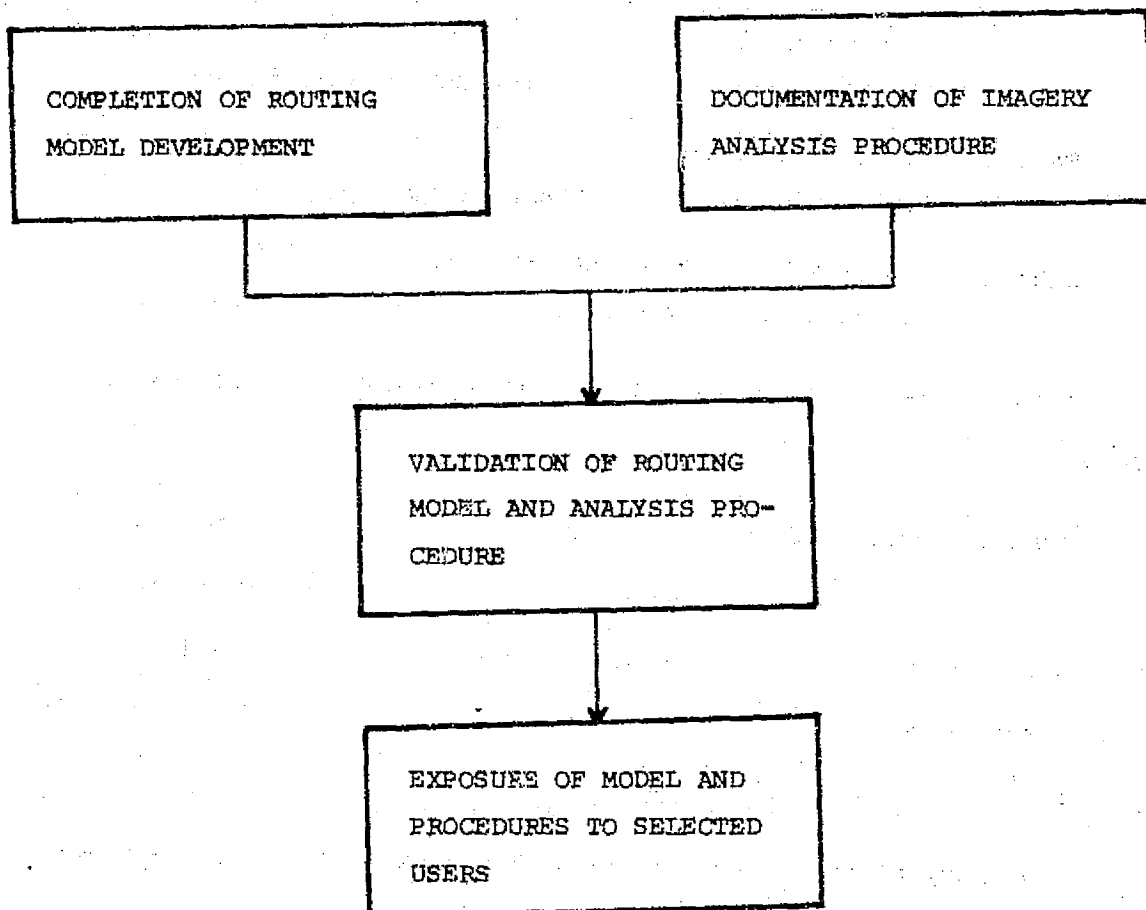
Figure 1 is a flow chart showing the objectives set out for this phase.

Task 1 constituted the synthesis of a routing module for the planning model. This has been completed and programmed in FORTRAN IV for operation on small-capacity digital computers. The model features user-interactive operation and amenability to present and potential inputs from satellite remote sensors.

A summary of its derivation is presented in Section VI. (A more detailed derivation is included in the Appendix). Task 1 culminated in the simulation of a peak runoff event as taken from actual gage records; this is also described in Section VI.

Task 2 involved the hydrologic land use classification of the Bucklodge Branch watershed in Montgomery County, Maryland. The techniques developed for Task 3 (described below) were applied to cover

FIGURE 1: FLOW CHART OF CURRENT PHASE



classification of Bucklodge Branch. This task also included the derivation of model parameters from the remotely sensed information. Results are reported in Section VI.

Task 3 resulted in the development of generalized procedures for extraction of quantitative information from LANDSAT imagery through simple visual analyses. The findings, given in Section V, showed that relatively uncomplicated techniques can yield results adequate for hydrologic modelling.

The final task included identification of prospective user groups and exposure of the model and associated analysis procedures to them. A summary of those activities is presented in Section VII.

V. PROCEDURES FOR EXTRACTION OF HYDROLOGIC DATA FROM LANDSAT IMAGERY

The quantities of rainfall which eventually become stream discharge depend in large measure upon the character and condition of the land surface over which it must run. Rain falling on a watershed is subjected to the retardant forces of the surface cover; this retardation, in turn, regulates the fractions of the water mass which run overland, infiltrate or are evaporated. A rural watershed covered with thick grass and trees, for example, will have a much different response to a peak rain event than will its urbanized counterpart.

Figure 2 exemplifies this effect. The curve shows the impact on runoff peak of altering the surface complex (as approximated by the S.C.S. curve number). Points on the curve were generated using a recorded rain event input to a 150 square kilometer basin in the region of Tuscany, Italy.* The sensitivity is marked. Figure 3, similarly, demonstrates the effect on the discharge peak of seasonal change, in this example, that of cultivating a portion of the watershed. Again the results are pronounced. Two conclusions can be made:

- 1) Surface cover is a significant driver of peak discharge event.
- 2) The provision of periodic land cover information can be of value to the hydrologic modeller.

* This watershed is currently being modeled for the government of the Region of Tuscany, Italy. The modeling techniques were derived from the present NASA - sponsored effort.

FIGURE 2: SENSITIVITY OF DISCHARGE TO SURFACE COVER

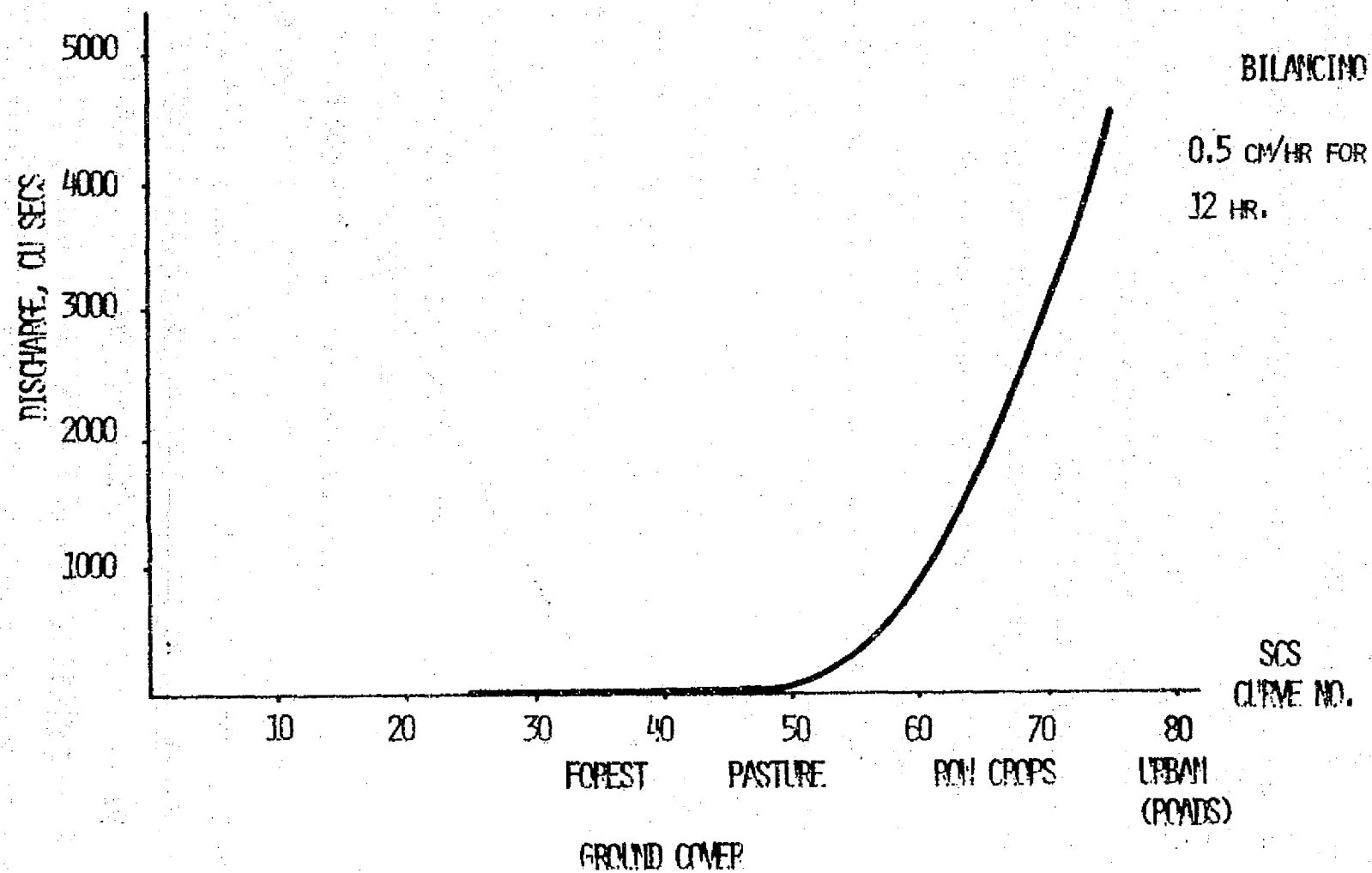
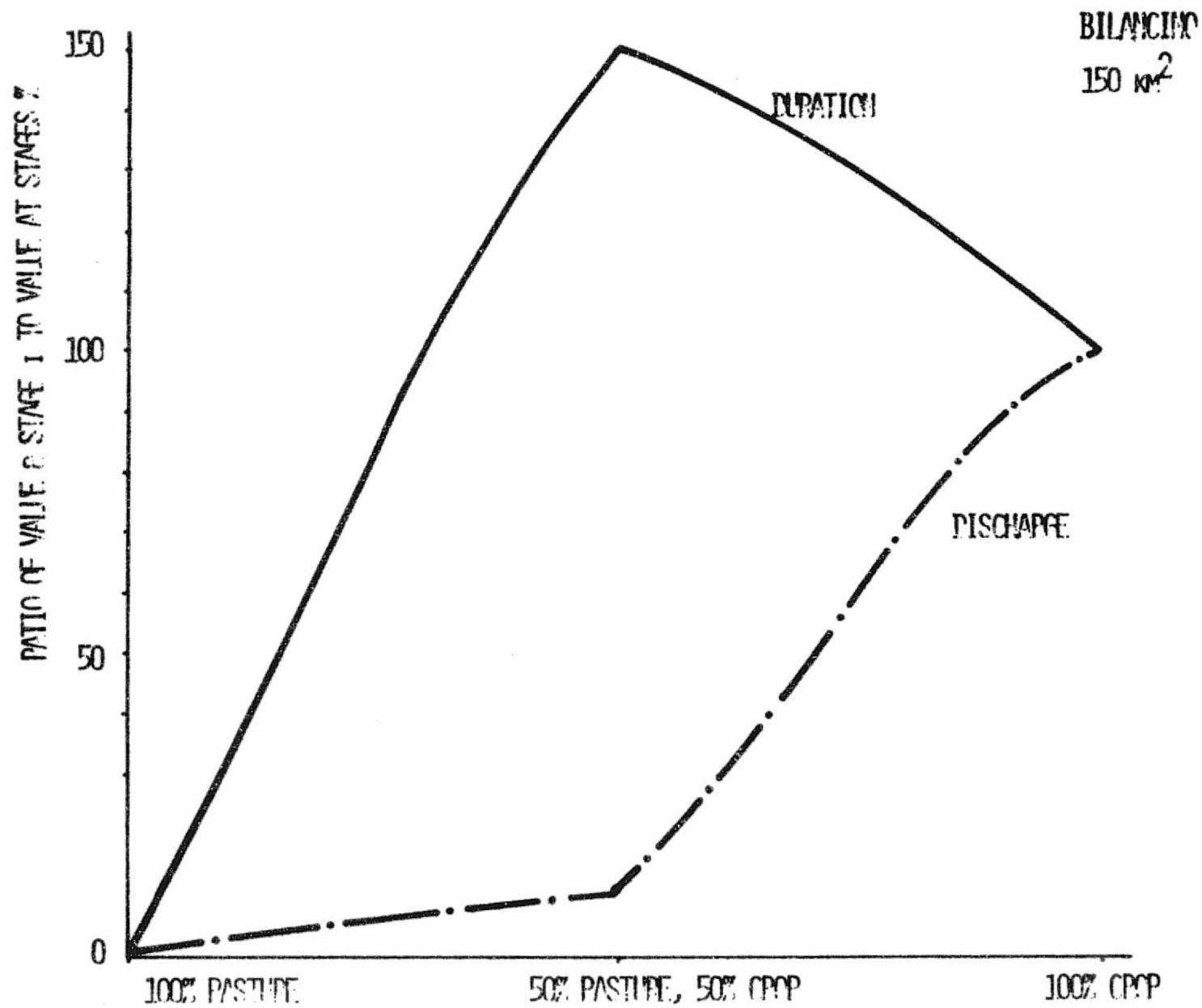


FIGURE 3 SENSITIVITY OF WATERBURY RESPONSE TO CHANGES IN VEGETATIVE COVER
FOR THE SAME PLANNING PAIR



Prior work in remote sensing for hydrology has shown that surface cover can be derived from presently available LANDSAT imagery. A problem with reducing potential to practice, however, has been the absence of standard procedures for extraction of required data by uncomplicated, inexpensive, yet accurate, means.

One objective of this effort was the development of procedures for utilizing LANDSAT data to determine watershed surface cover. An important result is that the procedure eventually developed is applicable not only to the specific model developed herein, but can be generalized to all hydrologic models.

5.1 Importance of Surface Cover to Hydrologic Models

For reasons just discussed, all but the simplest hydrologic models take surface cover into consideration. Specific implementations vary but generally include the following:

- a. Computation of initial detention storage
- b. Calculation of surface resistance to overland flow
- c. Division of the rainfall mass into its overland and infiltrated fractions
- d. Estimation of potential evapotranspiration
- e. Quantification of the effects of impermeable areas

Figure 4 summarizes the surface cover inputs to several widely-used hydrologic models. It is clear that a substantial amount of surface-related information is required.

MODELS	VARIABLES	SURFACE COVER	LAND USE/ LAND USE CHANGE	SURFACE WATER	IMPERMEABLE AREAS
USDAHL-70/74					
USGS					
UTAH STATE U.					
STANFORD MODEL					
TEXAS MODEL					
NOAA HYDRO 14					
NOAA HYDRO 17					
API					
SSARR					
COSSARR					
S,C,S, TR-20					
MUTCAT					

FIGURE 4: SURFACE COVER VARIABLES OF WATERSHED MODEL

For these requirements to be filled by LANDSAT, the frequency and resolution of the LANDSAT-derived data must be sufficient to meet model demands. With respect to the first point, LANDSAT can provide a new surface cover picture every nine to eighteen days. This frequency meets and exceeds all the requirements of current models, even when cloud occultation is factored in.

The resolution of land cover detail required by the models varies, but is generally consistent with the current capabilities of LANDSAT sensors. The exceptions are those models designed to analyze intra-urban hydrology; satellite data will be of limited applicability here. For those models suited to evaluation of larger watersheds, most requirements can be met through a LEVEL I* land use classification, which can be accomplished remotely. The modeller must be able to distinguish between:

- a. Urbanized areas
- b. Agricultural (cropped) areas/fallow
- c. Surface Water
- d. Pasture
- e. Forests

*(As defined in, "A Land-Use Classification System for Use With Remote Sensing Data," U.S.G.S. Circular 671, Anderson, Hardy, and Roach, 1972)

This level of detail will permit computation of friction factors such as Manning's "n," mensuration of impermeable areas; calculation of surface water area; etc.

5.2 Alternative Techniques for Analysis of LANDSAT Imagery

Because LANDSAT data is produced in two forms, computer compatible tapes (CCT's) and "photographic" images, two options for its analysis exist - computer and visual classification/mensuration. The first involves the development of mathematical/statistical algorithms for separation of themes based upon the relative output of each of the sensors. Visual analysis is the same with the exception that the algorithm is mental. The interpreter segregates on the basis of the individual or summed reflectance levels of the Multispectral Sensor Bands.

What are the advantages/disadvantages, if any, of either procedure? Our work in hydrology, and other application areas, has made obvious a number of factors making visual analysis preferable for "complex" scenes and low-cost applications. Principal among these are:

Training Sample Criteria

Computer classification and mensuration requires the establishment of a number of training samples. These should be "homogeneous" samples, containing at least a minimum number of pixels. With visual analysis, it is possible to minimize the training field requirement; it is also easier to account for variations within a theme which would result in errors with computer classification.

Maximization of Multi-Temporal Properties of LANDSAT Imagery

In hydrology, as well as agriculture, the use of multi-date imagery

has proved advantageous. Visual analysis facilitates the simultaneous evaluation of images from different seasons, years, etc., at low cost.

Ground Truth

In most settled areas, the scales of features vary significantly. The relatively low, 66 meter average resolution of LANDSAT causes boundary effects which distort the identification and mensuration of areas less than several tens of acres, if performed by automatic means. Only the visual overlay of aerial imagery or maps against LANDSAT imagery corrects this problem. Projection of visual images at scales which can be comfortably observed greatly facilitates scale matching.

Accuracy of Results

Except for LANDSAT scenes taken at the correct seasons when reflectance differences among the various ground covers are most pronounced and in which the features to be identified are extensive compared to the LANDSAT pixel dimensions, automatic classification exhibits considerable errors. Visual analysis employing one or more of the techniques indicated above (multitemporal, superposition with aerial photography), can result in significantly improved accuracies.

Equipment Requirements/Costs

The initial capital cost of visual analysis equipment (projectors, zoom transfer scopes) is considerably lower than that of digital processing equipment. For "complex" scenes, visual analysis has been found in this effort to cost on the order of 10% of computer analysis at equal performance. It is concluded that at the present state of the art, visual analysis techniques are preferable for small users, because they are more likely to utilize LANDSAT imagery if the initial costs and skills levels required

are kept as low as possible.

Even with simple visual means two problems still constitute impediments to the practical use of LANDSAT imagery: 1) the lack of a standard procedure; and 2) the unavailability of projection/analysis devices amenable to complete analysis of satellite imagery at low cost. ECOSYSTEMS¹ effort has resulted in techniques for solving both these problems.

A device for easy analysis was developed and tested* which is suited to LANDSAT scales and resolutions. It is described in Appendix B.

The following describes a recommended procedure for deriving quantitative hydrologic data from the MSS imagery.

5.3 Visual Extraction of Hydrologic Land Use from LANDSAT Imagery

The preceding sections have described the uses of surface cover data by hydrologic models, and indicated that many are obtainable from LANDSAT imagery. It is significant, in addition, that the extraction of these data can be accomplished through simple and inexpensive visual means, procedures similar to those used in analysis of aerial photographs. The development of a certain amount of expertise on the part of the interpreter is necessary, but the level required is not prohibitive. The most important concern is that a careful and consistent analysis procedure be adhered to, such as that described herein.

5.3.1 Land Use Information Content of the Four LANDSAT Bands

In order for LANDSAT data to be useful in hydrologic analysis:

* The device was developed on ECOSYSTEMS' own funds, but utilizing to the fullest the experience garnered in this NASA - sponsored effort.

resolution of the sensors must be sufficient to provide the required level of classification and area measurement; and, the optimum spectral bands must be chosen for the surface feature under study.

With respect to the first criterion, the minimum resolvable area of the LANDSAT sensors is of order 0.4 hectares (1 acre). The applicability of LANDSAT, therefore, will be optimized where the unit of analysis is sufficient, i.e. in medium to large-sized basins predominated by rural land use; it is in these basins, though, where gage records are typically less detailed and where modelling can have large benefits (snowmelt analysis, water works sizing, flood forecasting).

With respect to the second criterion, no single LANDSAT band can distinguish all land use classes well enough to meet the requirements of hydrologic modelling. However, the output from the four sensors taken individually and in sum do provide sufficient information. Each sensor sees a distinct spectral range and, therefore, receives different radiance levels from a particular object. For the purposes of thematic segregation, it is preferable that a sensor see a theme at one extreme of reflectance (i.e., very high or very low) while giving the opposite value for all other themes. This maximizes contrast and likewise the separability of the theme. Again, no single spectral band can accomplish this ideal case, but an examination of the imagery shows that hydrologic land use classes can be separated.

For example, in LANDSAT Band 7 (0.8 - 1.1 μ m) surface water appears very dark while its surroundings are generally much lighter whereas for Band 5, forested areas appear dark. Figure 5 illustrates this.

FIGURE 5

REFLECTANCE CHARACTERISTICS OF MSS BANDS



MSS BAND 5

(0,6 - 0,7 μm)

FOREST - DARK

MSS BAND 7

(0,8 - 1,1 μm)

SURFACE WATER - DARK

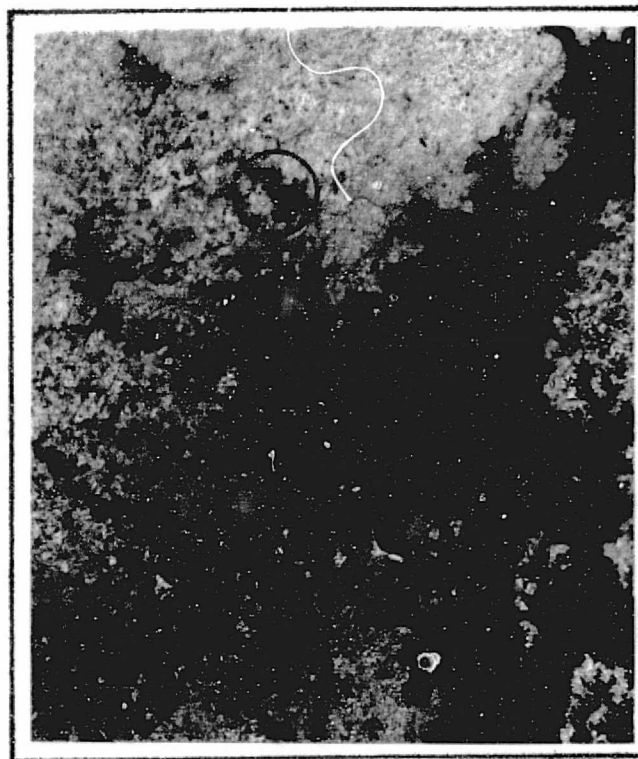


Table IV summarizes exemplary radiometric data and indicates which bands appear preferable for a given theme. The values, derived from imagery from the Baltimore-Washington area, show where the land uses fall on a fifteen-step gray scale. (A value of 1 \approx 100% reflectance; 15 \approx 0% reflectance). Themes will be most easily separated where the variance is small and where the other themes have different values.

5.3.2 Use of Composite Imagery

The utility of LANDSAT imagery can be augmented by combining the individual bands into composites. The addition of color to each band facilitates the separation of surface themes, because it allows the analyst to see the information contained in all bands simultaneously.

A simple, low cost procedure for color encoding individual black and white images and compositing them is available in the diazo process. Its best usage, as developed by ECOsystems, is to produce plastic transparencies in shades of a single color directly from LANDSAT 9" x 9" images. To accomplish this, the black and white image is sandwiched with a sheet of diazo film and exposed to ultraviolet light. The film is

TABLE IV

<u>BAND 4</u>		
	<u>OCT. '73 IMAGE</u>	<u>JUNE '73 IMAGE</u>
Surface Water	5-10	3-4
Urban	1- 7	1-2
Forest	10-11	7-8
Fields/Agricultural	4-13	1-9
<u>BAND 5</u>		
Surface Water	10-14	9-10
Urban	1- 4	1- 2
<u>Forest</u>	10-11	10-11
<u>Fields/Agricultural</u>	1- 7	1-12
<u>BAND 6</u>		
Surface Water	15	15
Urban	4-12	8-10
Forest	8- 9	5- 6
Fields/Agricultural	4-12	4-10
<u>BAND 7</u>		
<u>Surface Water</u>	15	15
<u>Urban</u>	10-11	10-11
Forest	7- 8	2- 5
Fields/Agriculture	2-11	1-11

 - indicates best single band for given theme

then developed by simple equipment which exposes it to ammonia vapors. Figure 6 exemplifies the process product: a diazo positive of a single-band - LANDSAT image processed in cyan. The procedure is repeated for the other bands producing each band in a different color. Finally, the diazo transparencies are overlaid, registered, and glued together to form the composite image. Figure 7 is a contact print of the resultant composite.

Several advantages to image analysis with diazo transparencies have been found:

1. The costs are very low, especially when compared to computer-aided classification techniques. The exposure and development unit can be purchased for approximately \$500 to \$1,000. The materials cost for composite transparencies is less than one dollar.
2. The diazo film yields a faithful positive reproduction of the original image. Very little detail is lost, and processing time is short. A composite transparency can be produced in under an hour.
3. By varying exposure times and film color, images can be "tuned" to accent desired features while depressing others. This significantly augments the separability of surface themes. Several composites can be prepared for a watershed, each of which optimizes the visibility of a specific land use.

5.4 Recommended Procedure for the Visual Analysis of LANDSAT Composite Imagery

The visual analysis of imagery for hydrologic land use should proceed in six steps:



FIGURE 6

BAND 7 DIAZO TRANSPARENCY ENCODED
IN CYAN, 6 OCTOBER 1973



FIGURE 7

SECTION OF CONTACT PRINT OF THREE BAND
DIAZO COMPOSITE, 6 October 1973

BAND 4 - YELLOW

BAND 5 - MAGENTA

BAND 7 - CYAN

- 1) Preparation of "tuned" Diazo Composites
- 2) Image Projection/Ground Truth Overlay
- 3) Watershed Delineation
- 4) Analysis of Ground Truth
- 5) Segregation of Surface-Cover Themes
- 6) Quantification of Hydrologic Parameters

5.4.1 Preparation of "Tuned" Diazo Composites

As noted earlier, no single LANDSAT band contains all the hydrologic information; each sensor maximizes the reflectance of the surface in a different spectral range. Full advantage of these reflectance differences has generally not been exploited in visual analysis: rather, past work has relied mostly upon LANDSAT's geometric properties - identification of shape and form from single color composites.

The diazo compositing process affords the analyst the opportunity to optimize the value of radiometric differences. Consider the following example: Band 5 (0.6 - 0.7 μ m) receives low reflectance from vegetation since these wavelengths are absorbed by chlorophyll. Band 7 (0.8 - 1.1 μ m), in contrast, receives nearly 50% of the incident radiation from mature green vegetation. This phenomenon can be exploited to discriminate vegetation.

Suppose that the watershed under study contains heavily vegetated areas. Is it possible to assign a desired color to these areas in preparing the composite.

If it is desired that these vegetated areas appear red, it is only necessary to encode the Band 5 diazo positive in red (and/or Band 4, if

it is used, since the two are correlated) and to develop Bands 6 and 7 in contrasting colors. The red vegetated areas of Bands 4 and 5 will show through the equivalent sections of Bands 6 and 7 which will be clear. The result is a composite "tuned" to vegetation.

Thus, by referral to the relative reflectances of land use classification, such as shown in Table 4, the analyst can compose his imagery to make more obvious the themes he wishes to identify. The technique described is valid for themes which provide high contrast (low or high reflectances simultaneously present). A modification of the process allows separation of themes whose reflectances lie closer together (lower contrast). It is a property of diazo imagery that increasing exposure time decreases the content of the image; i.e. a long exposure time drops out themes with high reflectance (low image density). A positive image can be color-encoded in a given color and exposed to the point where all areas with lesser density than those desired are eliminated. This procedure is then repeated with the equivalent negative image, but in a contrasting color. When the two images are overlaid, the subject then will appear in the color produced by combination: surrounding areas will be in pure hues. Figure 8 demonstrates the results.

The two techniques described above separate all but themes with very low relative contrast. To further improve the discrimination between these, a third option is the use of multi-temporal imagery. For example, forested areas and fields can have similar reflectances in all the MSS bands. Fields, however, are far less likely to display a signature which remains constant over the year. Figure 9 depicts an example. Note that in the February image the forest has lost its

FIGURE 8

TUNED DIAZO IMAGE - URBAN AREAS

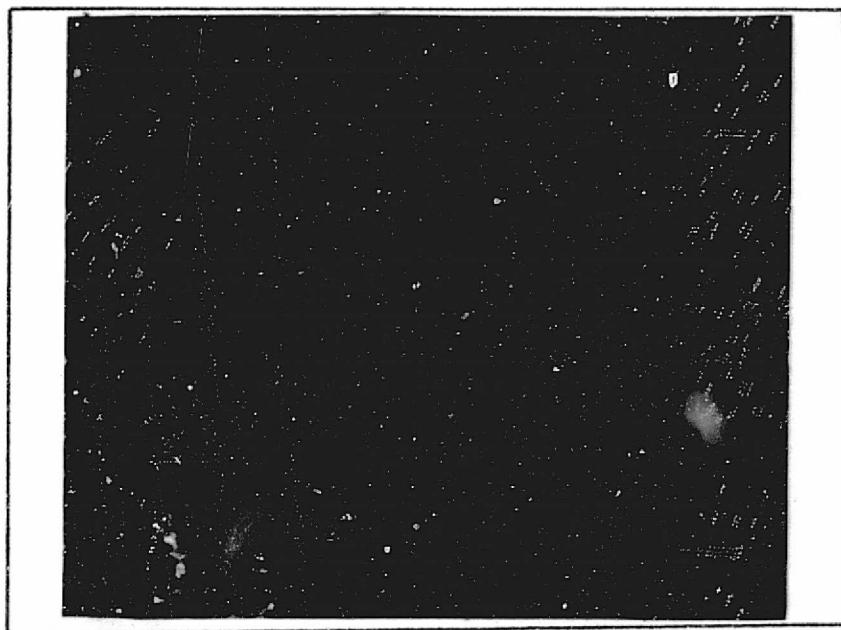


FIGURE 9: SEASONAL CHANGES IN FOREST SIGNATURE



OCTOBER 1973

LANDSAT 3 BAND COMPOSITE

FOREST CONTRAST LOW

FEBRUARY 1974
LANDSAT 3 BAND COMPOSITE

FOREST CONTRAST HIGH



similarity with fields.

A recommended procedure for integrating these techniques is to first develop a standard composite of bands and colors such as Band 4 (yellow), Band 5 (magenta) and Band 7 (cyan). The analyst should then separate all identifiable themes; the resultant classification can then be confirmed or adjusted by subsequent analysis of composites tuned to a particular theme from different seasons.

5.4.2 Image Projection

Land use classification to Level 1-2 requires significant magnification of the 1:1,000,000 scale LANDSAT imagery. This has previously been a drawback of visual analysis hardware - devices which could permit enlargement to greater than about 10X have been very expensive. The cost can be greatly reduced, however, as exemplified by the imaging system developed for such analysis by ECOSYSTEMS. Experience with this system has shown that magnifications of about 40X are convenient for land cover analysis, since they permit the direct overlaying of 1:1,000,000 LANDSAT images upon USGS 1:24,000 topographic maps. To insure the color-fastness of the images during analyses, color slides should be made from the diazo composite. The slides can be made to include as large an area as desired, but it is preferable to reproduce the diazos at one-to-one scale. The area represented in a 35-millimeter, 1:1 from a 1:1,000,000 LANDSAT image will be approximately 86,500 hectares. Larger watersheds can be analyzed in sections.

The slides are made with a 35 millimeter single lens reflex camera equipped with a bellows. The diazo composite is illuminated from behind by a light source matched to the color temperature of the slide film used. The photographs are taken with the camera mounted on a copy stand. Once exposed, nearly all slide films can be developed "in-house" using inexpensive chemistry. The time required from exposure to projector-ready slide is less than two hours.

Finished slides are mounted in the imaging system and projected. As shown in Figure 10 , the analysis table is equipped with an overhead mirror which reflects the image onto a work surface. The LANDSAT image can thereby be superimposed over maps or aerial photographs. A zoom control allows the scales of the projected image and ground truth to be matched.

5.4.3 Watershed Delineation/Ground Truth Overlay

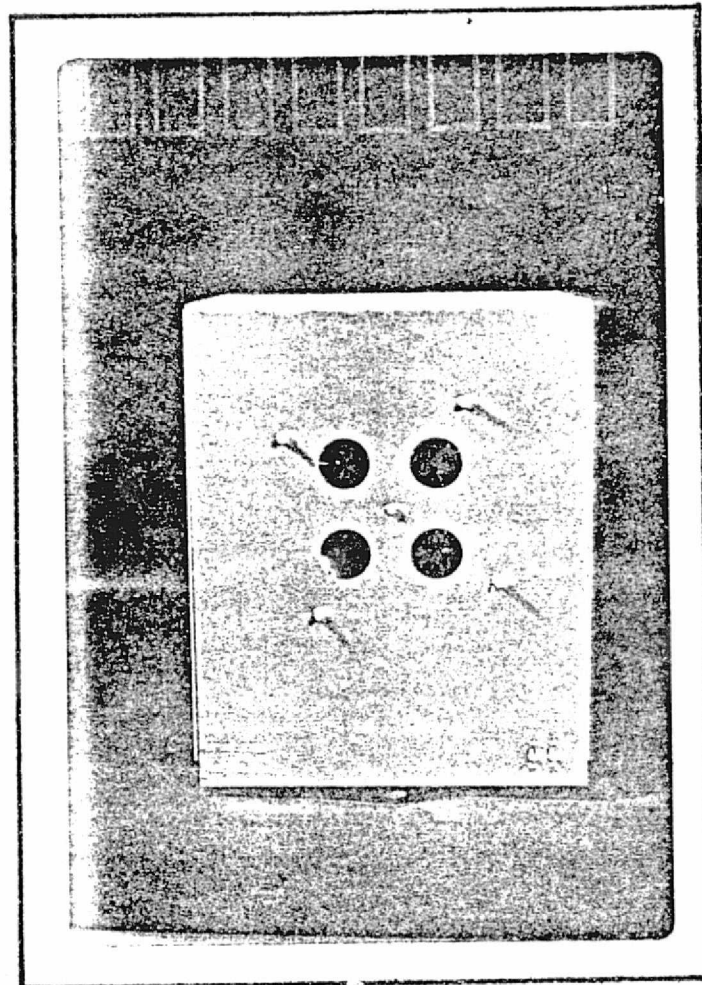
Analysis of hydrologic land cover begins with the demarcation of the boundaries of the watershed. Except in regions of very high relief, some ancillary information is generally required. This is readily available in the form of USGS topographic maps. Stereo aerial photographs, where available, can also be used. The watershed ridge line is first traced on the map. The LANDSAT image is projected over the map and aligned using roads, rivers, lakes, or other prominent features for reference. A sheet of tracing paper is placed over both and the ridge line drawn on it. The map is then removed.

5.4.4 Analysis of Ground Truth

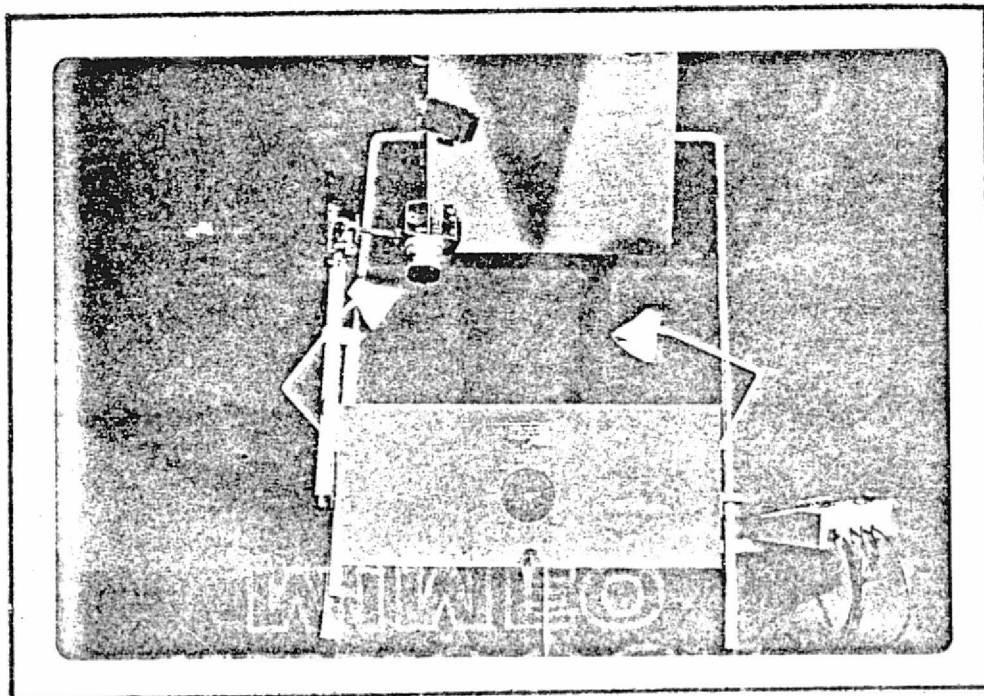
There are a number of widely-available sources of ground truth which can be valuable aids to the interpretation of satellite imagery.

FIGURE 10

ECOSYSTEMS IMAGE ANALYSIS DEVICE



PROJECTION
UNIT



ANALYSIS
TABLE

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Among these are:

- 1) topographic maps (USGS)
- 2) soil surveys (SCS)
- 3) aerial photographs

Topographic maps, though often dated, contain some land cover information. Specifically, forested areas, lakes, streams and urban areas are called out. Soil Conservation Service maps are most valuable to estimation of the subsurface characteristics of a watershed but also show streams, roads, surface water. Many have the soil classes drawn up on aerial photographs which may be used as ground truth if better ones are not obtainable. Low altitude aerial photographs are the best source of ground truth, but are also the more expensive and least available.

What are the optimum uses of ground truth, and how would one proceed to analyze land cover without it? In the absence of any ancillary data whatsoever, it would be necessary to rely totally upon the radiometric characteristics of the LANDSAT sensors. Even in this case, it is possible for a great deal of land cover information to be culled out. Visible themes such as rivers and lakes, some urban areas, and forests can be identified by their shape and form. An interpreter with some knowledge of the study area and of the spectral properties of land use themes could add another level of information. This, in effect, would be the same as checking LANDSAT data against a training field. Familiarity with the seasonal or phenologic progressions of vegetation is also most valuable.

A competent interpreter can generally adequately classify hydrologic land use to Level 1-2 using only LANDSAT imagery. The existence of

certain types of ground truth facilitates the process and should be taken advantage of. Maps and photographs, even if outdated, can be used to verify that an area classified as forest is, indeed, forest. If such fact can be confirmed within the watershed, or even in a nearby location, the results of these "tests" can be extended over the study area, e.g. if a red-blue area in the LANDSAT image is determined to be forest, areas of like color can also be classified as forest. The resultant classification can be spot-checked where the presence of true forest areas is known.

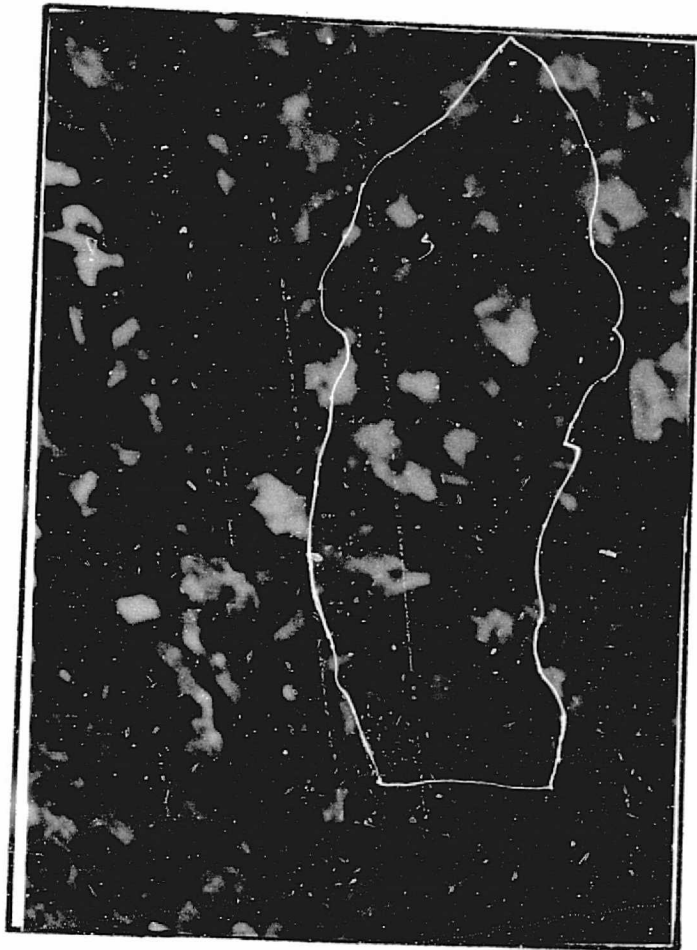
Prior to evaluation of the LANDSAT images, all available ground truth should be collected. The data obtained should be summed into a base map for the basin. All surface features discernible from the ground truth should be designated on the map. In the ideal case, ground truth is sufficiently complete to designate a gross, even though mostly outdated, land use map for the entire basin; the function of the LANDSAT data, in this case, is to update the older information and to provide the important seasonal information which it lacks.

5.4.5 Classification of LANDSAT Themes

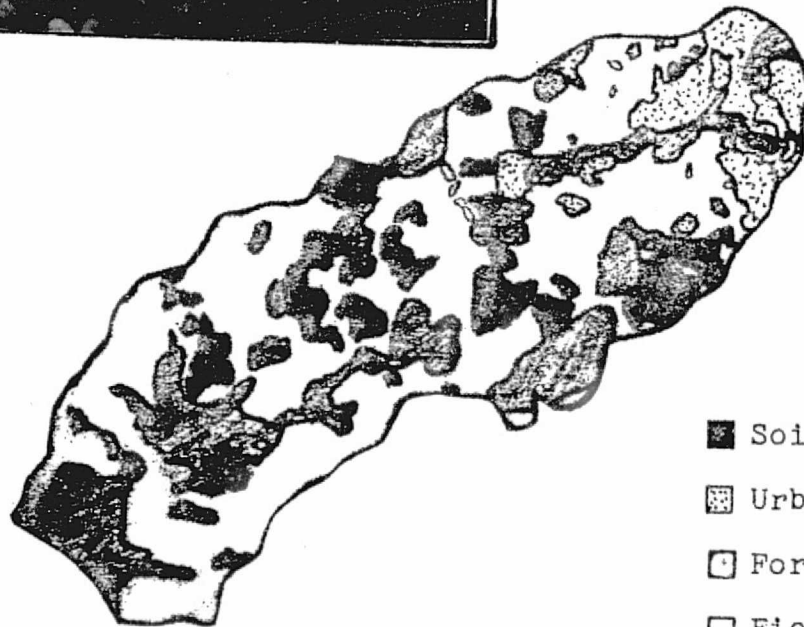
The next step in surface cover analysis is the actual classification of themes from the diazo composite. The image has been projected on the work surface and the watershed boundaries established. The analyst must then determine how many separable themes, or colors, exist within the scene. Figure 11 exemplifies the process. The analyst should make a tracing of the themes which are identifiable. Once drawn, it is helpful to assign an identifier to each area delineated and identified; it is suggested that this be accomplished through comparison with a set of standard color chips such

FIGURE 11

SEPERATION OF LAND USE THEMES



MUDDY BRANCH BASIN
LANDSAT
6 OCT, 73



- Soil
- ▣ Urban
- ▣ Forest
- ▣ Fields
- ▣ Lakes

as those used in aerial photographic interpretation. Each separable color is thereby given a unique label; this insures repeatability and also facilitates validation by other interpreters.

At this point the analyst has a map divided into color themes but has not as yet identified what the colors represent. To do this, he refers to the available ground truth; selects a test area from within each color class; compares it to the maps or photos, and assigns the area to a land use designation as in Figure 12. The resultant land use map should be regarded as still tentative. The classifications are subject to modification using composites of different composition, i.e. different tuning, or from different seasons. Generally, initial classification reveals differences between the LANDSAT imagery and the ground truth due to changes more recent than are reflected in the maps or photos; these can be confirmed by reference to additional images.

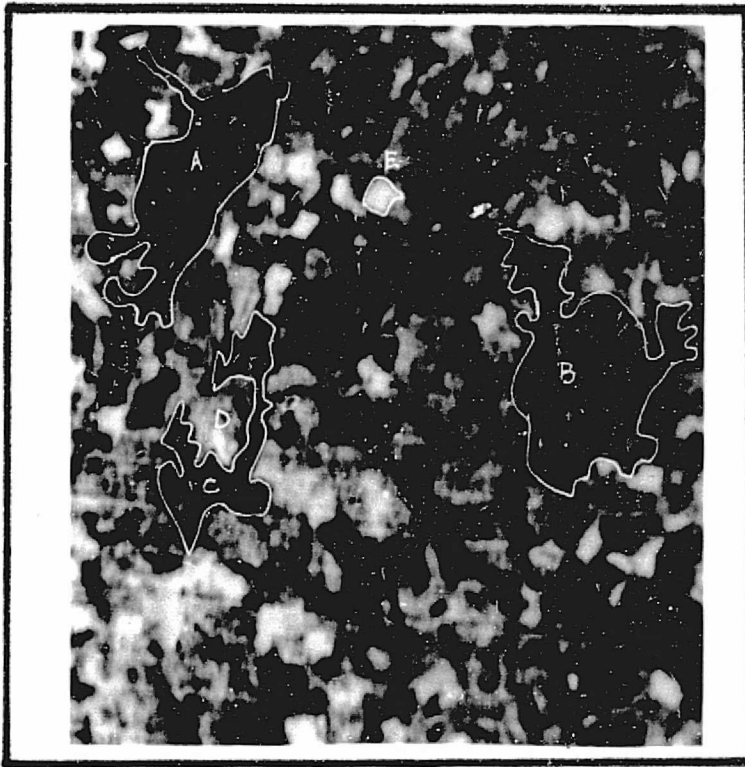
The result of multiple-image classification will be a hydrologic land use map suitable for the derivation of quantitative model parameters.

5.4.6 Quantification of Hydrologic Parameters

With the land use map in hand, the derivation of model parameters can proceed as it would using any source of surface cover data. The exact procedure will vary with the model used; the following paragraph describes a generalized technique used by several models - the computation of an average value of Manning's "n" for a subwatershed.

Planning models often require the division of watersheds into hydrologically homogeneous sub-areas. The criteria for defining

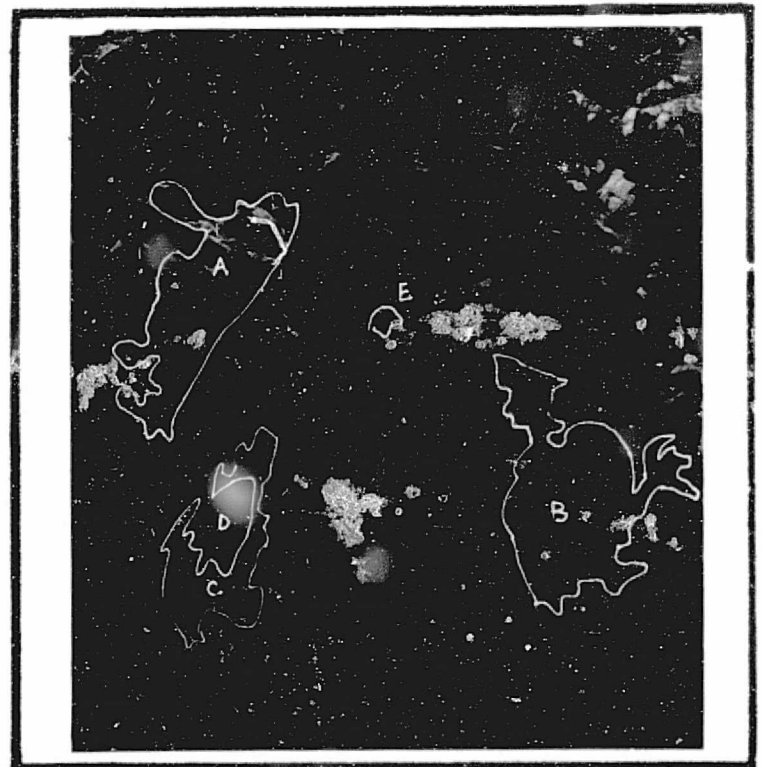
FIGURE 12: CLASSIFICATION OF LAND USE THEMES



LANDSAT
3 BAND COMPOSITE
OCTOBER 1973

A, B, and C Indicate Forest
D and E Indicate Fields

AERIAL COLOR - IR
DECEMBER 1973

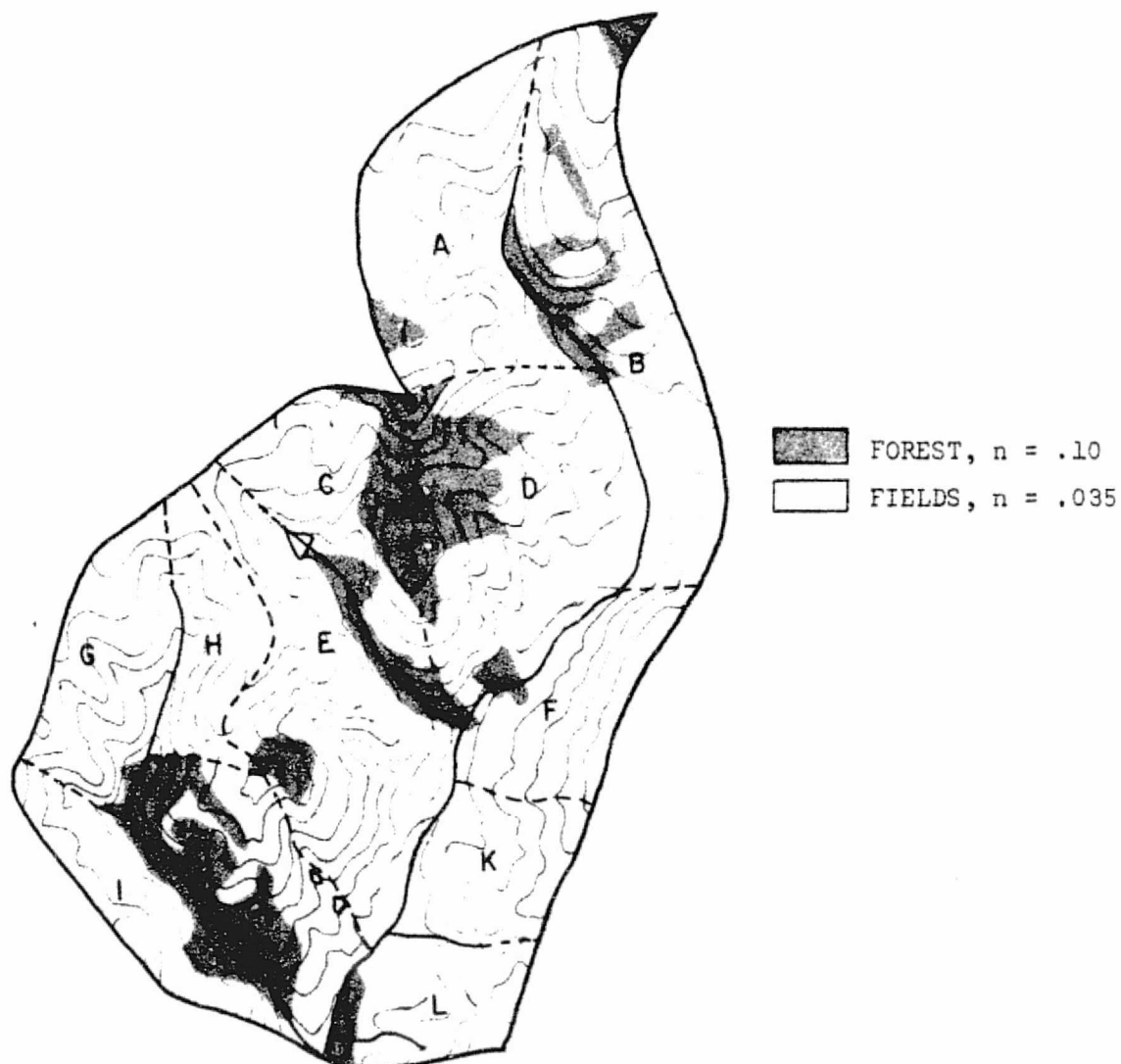


homogeneity include topography, soil characteristics, and surface cover. Typically, maps of each are prepared and compared in overlay fashion. The modeller then divides the watershed to give the optimum uniformity among these three parameters. Figure 13 demonstrates the process.

Once the homogeneous sub-areas are established, an average set of parameters is assigned to each. With respect to surface cover, an average surface friction factor, such as Manning's "n," is computed for every sub-area. Figure 14 shows how this is accomplished from the LANDSAT map as well as from aerial photography. First, the sub-areas are delineated on the land cover map. Then the percentage of its area covered by each use is computed using a calibrated grid, as shown, or a planimeter. Finally, the percentages computed are compared to a table of values for Manning's "n" as reproduced in the figure. Their computed weighted average becomes the average friction factor for the sub-area. Parallel analyses of LANDSAT and aerial images, performed during this effort, yield nearly identical values for surface friction.

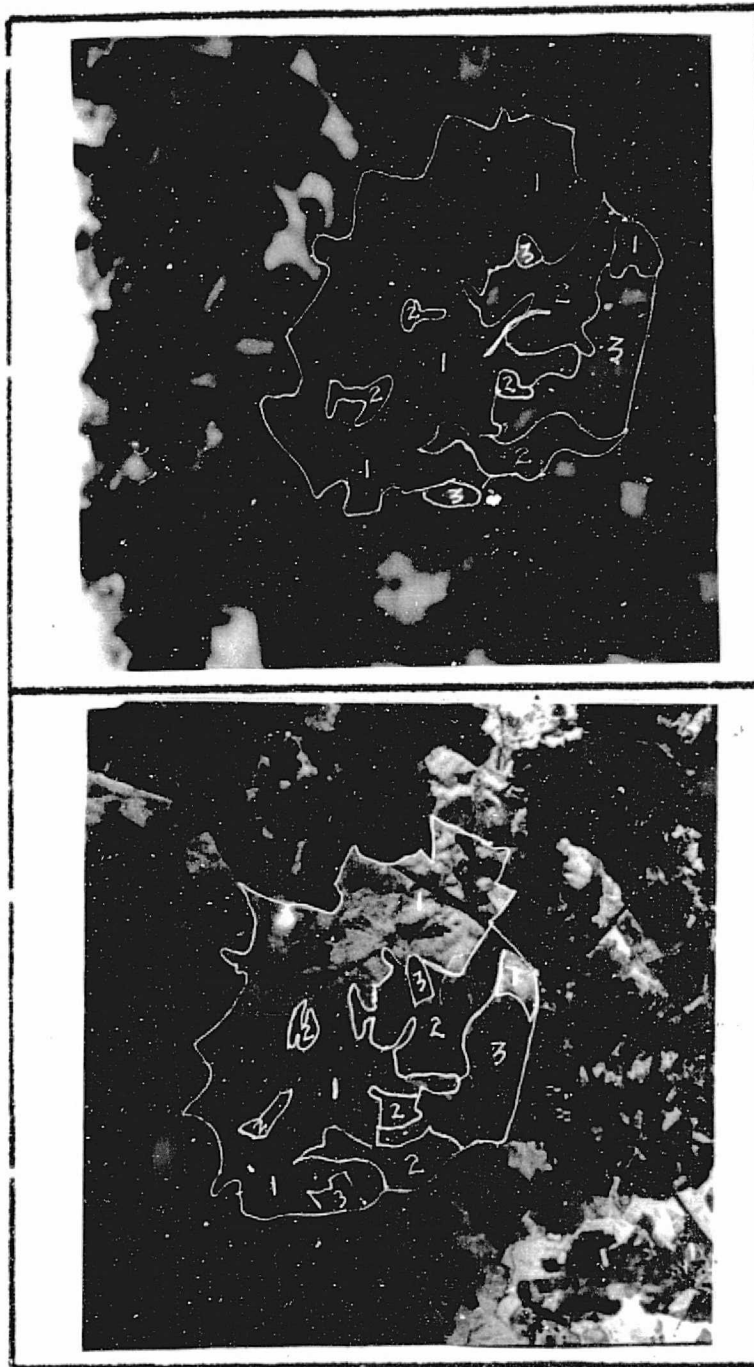
These values become direct inputs to planning models. The following section demonstrates the application of the techniques described to an actual watershed.

FIGURE 13 DIVISION OF A WATERSHED INTO HYDROLOGICALLY HOMOGENEOUS SUB-AREAS



SUBBASIN	AVG. "n"	AVG. SLOPE M/M	AVG. INFIL. (range) cm/hr.	AVG. SOIL MOISTURE CAP. cm.
A	.040	.050	2.5 - .25	7.6
B	.056	.055	5.1 - .5	7.6
C	.068	.055	.25 - .03	1.3
D	.056	.075	1.3 - .05	2.5
E	.044	.080	1.3 - .05	2.5
F	.038	.080	5.1 - .5	7.6
G	.038	.070	.25 - .03	1.3
H	.035	.110	1.3 - .05	2.5
I	.053	.105	1.3 - .05	2.5
J	.064	.085	5.1 - .5	7.6
K	.035	.060	.25 - .03	1.3
L	.045	.055	1.3 - .05	2.5

FIGURE 14: ASSIGNMENT OF HYDROLOGIC PARAMETERS



LANDSAT COMPOSITE
OCTOBER 1973

1 = FOREST
2 = FIELDS
3 = URBAN

AERIAL COLOR IR
DECEMBER 1973

	% FORESTS n = .1	% URBAN n = .01	% FIELDS n = .03	AVERAGE "n"
AERIAL	67	12	22	.075
LANDSAT	65	11	24	.073

VI. DEVELOPMENT OF REMOTE SENSING MODEL AND APPLICATION TO TEST WATERSHED

6.1 Model Development

During the course of this project, several criteria for planning models using remote sensing were developed. They include:

- 1) The model should consider all hydrologic "drivers," i.e., the surface and sub-surface processes which significantly affect the discharge peak rate and duration.
- 2) It should take maximum advantage of presently feasible remote sensing inputs (surface cover) and be amenable to new ones (soils, soil moisture, etc.) as they are developed.
- 3) A principal function of the study should be to demonstrate to prospective users of LANDSAT data how remote sensing techniques can be applied to the general class of planning models with actual watershed data.

A model has been deduced from standard practice and modified to a form consistent with these criteria. It simulates the flow of rain-water over the surface of a watershed, subjects it to subsurface abstraction (using the Holtan infiltration formula); and routes the excess through stream channels to the outlet. Surface cover, land use, soil type, soil moisture content, basin and channel physiography and topography are explicitly considered.

As presently configured, the model consists of an overland flow and a channel flow module. The overland component is based on the conservation of rainfall volume:

$$V = qt - I$$

where;

V = overland flow volume, m^3

q = rain rate, m^3/sec ,

I = total infiltration volume, m^3

t = rain duration, secs.

The volume of runoff over time is defined by the Manning relation for surface flow:

$$Q = \frac{\sqrt{s}}{n} (y)^{2/3}$$

where;

Q = surface runoff, m^3/sec

s = slope, m/m

n = Manning's surface friction coefficient

y = depth of overland flow, m

The model operates in discrete time steps, computing a depth value (y) for the beginning and end of each interval and using their average to calculate a discharge (Q). The Q values for all time steps constitute the overland flow hydrograph,

The channel flow module takes the overland hydrographs from homogeneous sub-areas of a watershed and routes them to the outlet. Manning's relationship is used to compute channel outflow. Figure 5 summarizes the model's components; a logic flow diagram and a FORTRAN listing are included in the Appendix, Table 5 lists the input data required by the model.

FIGURE 15
REPRESENTATION OF ECOSYSTEMS MODEL COMPONENTS

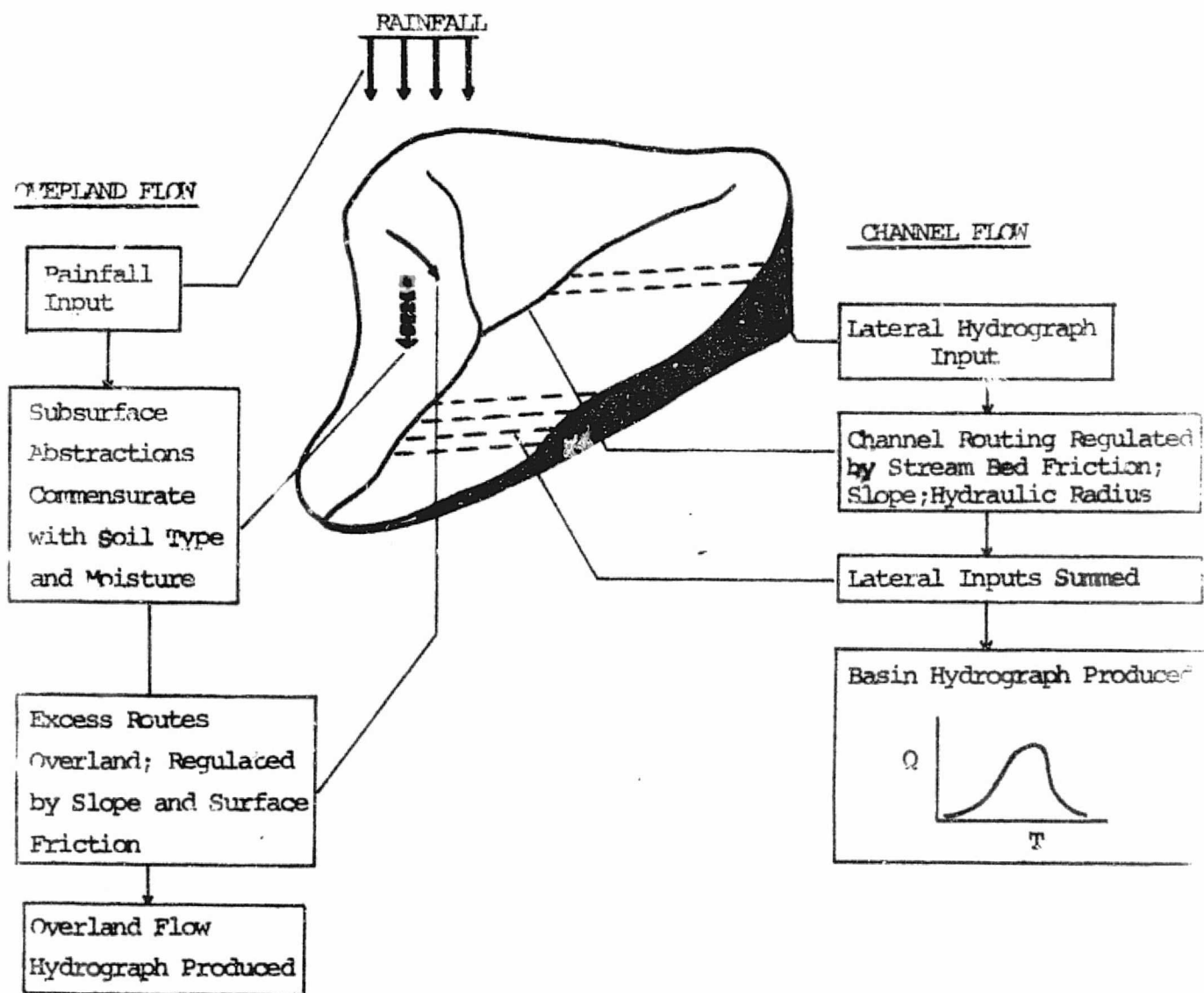


TABLE 5

SUMMARY OF ECOSYSTEMS' MODEL INPUTS

<u>OVERLAND FLOW PARAMETERS</u>	<u>CHANNEL FLOW PARAMETERS</u>
Unit strip length, meters	Channel length, meters
Unit strip slope, meters/meter	Channel slope, meters/meters
Unit strip Manning's "n"	Channel Manning's "n"
Initial depth of flow, meters	Channel Hydraulic radius, meters
<u>SOIL PARAMETERS</u>	
Soil moisture capacity, meters/meter	
Antecedent moisture content, meters/meter	
Percolation rate, meters/sec.	
Steady-state infiltration rate, meters/sec.	
<u>OVERLAND FLOW INPUTS</u>	<u>CHANNEL FLOW INPUTS</u>
Rainfall temporal profile	Unit strip Hydrographs
Rain rate (m/sec)	Discharge, m ³ /sec
Time (secs)	Time, secs

The parameters are input in the conversational mode, i.e., the program "asks" the modeller to enter each one as required. The output of the overland flow module is printed in tabular form and there is an option to graph the data. A sample run is shown in Figure 16.

6.2 Application of the Model to Test Watersheds

Tests were run using LANDSAT data as inputs to verify the operation of the model for typical ungaged watersheds. The tests served two purposes :

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ENTER LENGTH(M); SLOPE; MANNINGS N
 ?0024.61.0050.0113
 ENTER TIME STEP INCREMENT(SECS) AND NO. OF TIME STEPS
 ?010.010
 ENTER TOTAL TIME LIMIT (SECS)
 ?001000
 ENTER NUMBER OF RAIN INCREMENTS
 ?002
 ENTER SOIL MOISTURE CAPACITY(M); ANTECEDENT MOISTURE(M); PERC(M/SEC); FINAL INFIL.(M/SEC)
 ?0.05000.0000.0000000000.000000
 ENTER RAIN RATE(M/SEC) AND DURATION(SECS)
 TOTAL RUN TIME MUST BE ACCOUNTED FOR
 ?.000004620500.
 ?.000002310000.

TIME (SECS)	RAIN (M3/SEC)	INFIL. (M3/SEC)	H (M)	FLOW (M3/SEC)	CAP. (M)
100.00	.0000462000	.0000173968	.0040939003	.0001976121	.0403938269
200.00	.0000462000	.0000165467	.0047137964	.0004514202	.0466927179
300.00	.0000462000	.0000157493	.0030600260	.0006136466	.0450742096
400.00	.0000462000	.0000150007	.0037341554	.0007004600	.0435331874
500.00	.0000462000	.0000142972	.00400823025	.0007477077	.0420649610
600.00	.0000231000	.0000136356	.0047230426	.0004524591	.0406651907
700.00	.0000231000	.0000130129	.0057176463	.0003452210	.0393290045
800.00	.0000231000	.0000124262	.0052040123	.0003026943	.0380550250
900.00	.0000231000	.0000118732	.0051271990	.0002877694	.0368373070
1000.00	.0000231000	.0000113514	.0051007737	.0002860443	.0356736705

ENTER MAXIMUM DISCHARGE - XX.XX
 ?00.0015
 ENTER TIME SCALE STEP (SECS)
 ?020

SAMPLE OUTPUT OF STRIP HYDROGRAPH MODEL

FIGURE 16

+ INDICATES INFILTRATION
 * INDICATES DISCHARGE
 # INDICATES RAINFALL

TIME (SECS)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)	DISCHARGE (MC/SEC*12 -4)
	0.00	1.50	3.00	4.50	6.00	7.50	9.00	10.50	12.00	13.50	15.00
0.	I	I	I	I	I	I	I	I	I	I	I
20.	I*	I	I	+	I	I	I	I	#	I	I
40.	I *	I	I	+I	I	I	I	I	#	I	I
60.	I	*	I	+I	I	I	I	I	#	I	I
80.	I	*	I	+I	I	I	I	I	#	I	I
100.	I	I	*	I	I	I	I	I	#	I	I
120.	I	I	+	I	I	I	I	I	#	I	I
140.	I	I	*	+I	I	I	I	I	#	I	I
160.	I	I	I	* +I	I	I	I	I	#	I	I
180.	I	I	I	*	I	I	I	I	#	I	I
200.	I	I	I	+	I	I	I	I	#	I	I
220.	I	I	I	+	I	*	I	I	#	I	I
240.	I	I	I	+	I	*	I	I	#	I	I
260.	I	I	I	+	I	*	I	I	#	I	I
280.	I	I	I	+	I	*	I	I	#	I	I
300.	I	I	I	+	I	*	I	I	#	I	I
320.	I	I	I	+	I	*	I	I	#	I	I
340.	I	I	I	+	I	*	I	I	#	I	I
360.	I	I	I	+	I	*	I	I	#	I	I
380.	I	I	I	+	I	*	I	I	#	I	I
400.	I	I	I	+	I	*	I	I	#	I	I
420.	I	I	I	+	I	*	I	I	#	I	I
440.	I	I	I	+	I	*	I	I	#	I	I
460.	I	I	I	+	I	*	I	I	#	I	I
480.	I	I	I	+	I	*	I	I	#	I	I
500.	I	I	I	+	I	*	I	I	#	I	I
520.	I	I	I	+	I	*	I	I	#	I	I
540.	I	I	I	+	I	*	I	I	#	I	I
560.	I	I	I	+	I	*	I	I	#	I	I
580.	I	I	I	+	I	*	I	I	#	I	I
600.	I	I	I	+	I	*	I	I	#	I	I
620.	I	I	I	+	I	*	I	I	#	I	I
640.	I	I	I	+	I	*	I	I	#	I	I
660.	I	I	I	+	I	*	I	I	#	I	I
680.	I	I	I	+	I	*	I	I	#	I	I
700.	I	I	I	+	I	*	I	I	#	I	I
720.	I	I	I	+	I	*	I	I	#	I	I
740.	I	I	I	+	I	*	I	I	#	I	I
760.	I	I	I	+	I	*	I	I	#	I	I
780.	I	I	I	+	I	*	I	I	#	I	I
800.	I	I	I	+	I	*	I	I	#	I	I
820.	I	I	I	+	I	*	I	I	#	I	I
840.	I	I	I	+	I	*	I	I	#	I	I
860.	I	I	I	+	I	*	I	I	#	I	I
880.	I	I	I	+	I	*	I	I	#	I	I
900.	I	I	I	+	I	*	I	I	#	I	I
920.	I	I	I	+	I	*	I	I	#	I	I
940.	I	I	I	+	I	*	I	I	#	I	I
960.	I	I	I	+	I	*	I	I	#	I	I
980.	I	I	I	+	I	*	I	I	#	I	I
1000.	I	I	I	+	I	*	I	I	#	I	I

FIGURE 16 (cont'd)

1. To substantiate that the model is capable of producing satisfactory results as compared to similar models of ungaged watersheds. The watershed used was gaged and these records were used for comparison.
2. To demonstrate for prospective users of LANDSAT data that the analysis techniques described in Section IV are applicable in "hands-on" hydrologic modeling and provide sufficient improvement to warrant their use.

The simulation test encompasses two phases: data collection and reduction, and the actual model runs.

6.2.1 Data Collection and Reduction

The first step of this phase was the selection of a test watershed. After study, the Bucklodge Branch basin, in Montgomery County, Maryland, was selected. The advantages of this site were:

1. Sufficient rainfall and streamflow records were available to validate the model's results.
2. The watershed contains several distinct land uses providing a good test of what can be distinguished from LANDSAT.
3. Aerial photography ground truth existed to validate the results of LANDSAT analysis.
4. The proximity of Bucklodge Branch permitted any moot points to be resolved by field survey.

Bucklodge Branch drains approximately twenty three square kilometers (9 square miles) of an urban/rural setting in Montgomery County, Maryland. The overall stream length is 32 kilometers (20 miles). The predominant land uses are rural and agricultural, including fields, forests, bare soil, surface water, and a small urbanized area. These land uses are typical of those of ungaged watershed where satellite analysis will have the most value. Bucklodge Branch is monitored by the Montgomery County Department of Environmental Protection and is equipped with two raingages and a river stage recorder. Figure 17 is a map of Bucklodge, showing the locations of the gaging sites,

The table contained in Section 6.1 listed the data which were required before the model could be run. Since the purpose of this project was to rely minimally upon non-satellite data, only data sources readily and widely available were called upon. The soils parameters, infiltration and percolation rates, were taken directly from the Soil Conservation Service survey of Montgomery County. Figure 18 exemplifies the available soils data. Slopes and lengths were measured from a U.S. Geological Survey 1:24,000 scale topographic map. Land cover data was derived solely from LANDSAT imagery. The resulting classification was verified by comparison with 1:130,000 color infrared aerial photography.

The LANDSAT imagery selected for evaluation was dated 6 October 1973. It was chosen for image quality and temporal proximity to the aerial photographs (December 1973). Multi-spectral sensor bands 4 (0.5-0.6 μm), 5 (0.6-0.7 μm) and 7 (0.8-1.1 μm) were combined in a three-band diazo

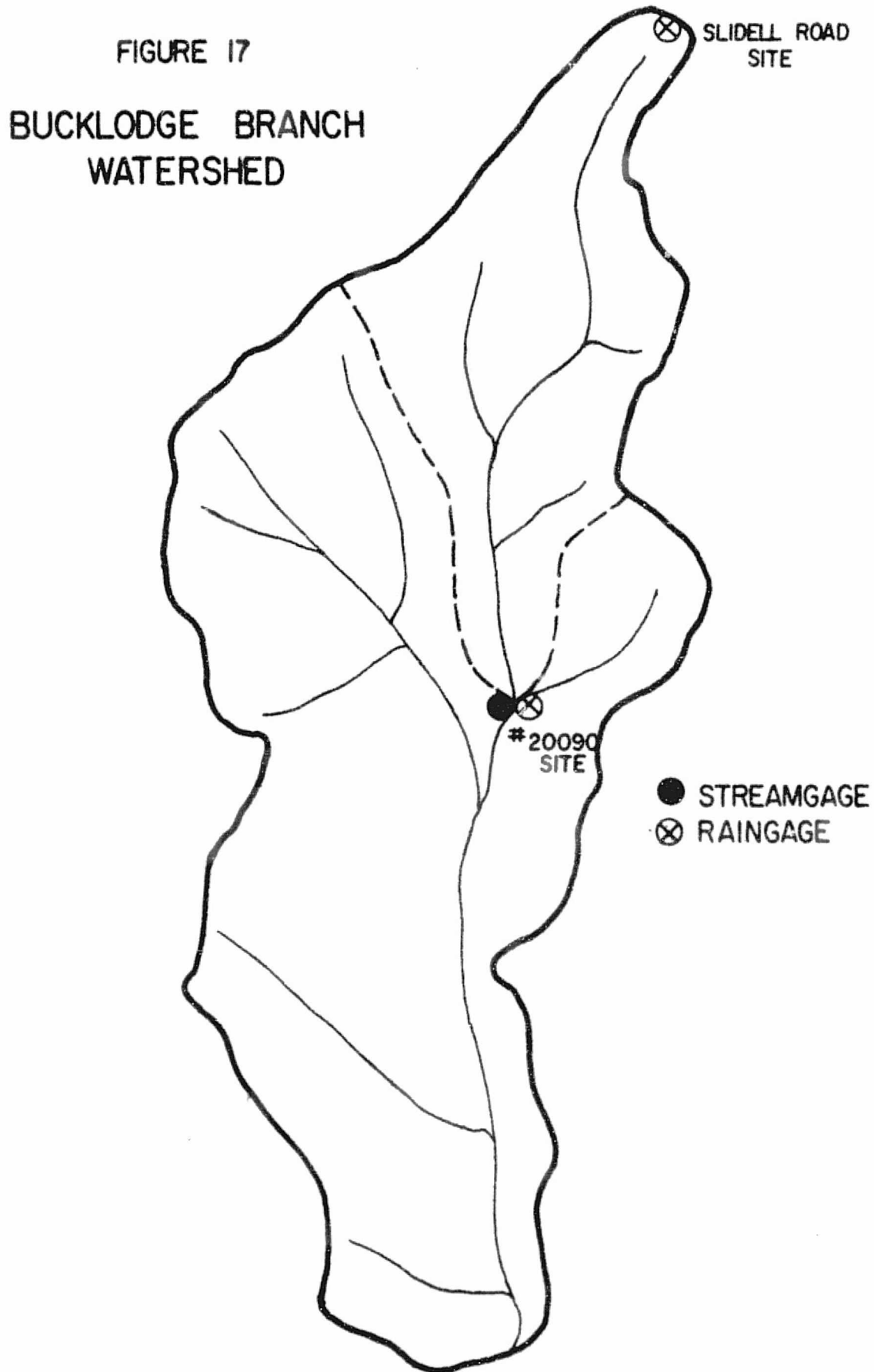


FIGURE 18

EXERPT FROM S.C.S. SOIL SURVEY OF MONTGOMERY CO., MD.

Map symbol	Soil	Depth to seasonally high water table	Depth to bedrock	Brief description of site and soil	Depth from surface (typical profile)	USDA (textural class)
GmA	Glenville silt loam, 0 to 3 percent slopes.	<i>Feet</i> 1 to 3	<i>Feet</i> 4+	Moderately well drained soils in draws and depressions and upland flats; developed in residuum weathered from crystalline rocks; some colluvial surface material. Seepage spots fairly common. Fragipan in subsoil.	<i>Inches</i> 0 to 5	Silt loam----
GmB	Glenville silt loam, 3 to 8 percent slopes.	1 to 3	4+		5 to 28	Silt loam----
GmB2	Glenville silt loam, 3 to 8 percent slopes, moderately eroded.	1 to 3	4+		28 to 42+	Silt loam----
Gr	Gullied land, Penn materials----	(?)	0 to 2	Very severely eroded areas that originally were Penn silt loam or undetermined soils of the Penn series; very shallow; in many places bedrock is exposed. Well-drained, deep soils on flood plains; developed in alluvium derived from limestone. Infrequently flooded.	0 to 10 10+	Channery silt loam-----
HaA	Huntington silt loam, 0 to 3 percent slopes.	3	(?)		0 to 12	Silt loam-----
HaB2	Huntington silt loam, 3 to 8 percent slopes, moderately eroded.	3	(?)		12 to 60+	Silt loam-----

Engineering classification		Percentage passing—			Selected characteristics significant in engineering				
Unified	AASHO	No. 200 sieve	No. 10 sieve	No. 4 sieve	Range in permeability	Structure	Reaction	Dispersion	Shrink-swell potential
ML-----	A-4-----	65	90	95	<i>Inches per hour</i> 0.33 to 2.0	Granular to subangular blocky.	^{pH} 4.5 to 5.5	Moderate----	Low.
ML or CL--	A-4 or A-6--	70	95	98	.06 to 2.0	Platy and subangular blocky.	4.5 to 5.0	High-----	Low.
MH-----	A-5-----	65	85	90	.20 to 0.63	Subangular blocky-----	4.5 to 5.0	High-----	Low.
ML or GM--	A-2 or A-4--	35	50	60	.20 to 2.0	Subangular blocky-----	4.5 to 5.0	High-----	Low.
GM or GC--	A-2-----	15	20	30	-----	(Fractured shale)-----	-----	-----	-----
ML-----	A-4-----	80	100	100	.63 to 2.0	Granular to platy-----	0.1 to 5.5	Moderate----	Low.
ML or CL--	A-4 or A-6--	90	100	100	.20 to 0.63	Blocky and subangular blocky.	6.1 to 7.4	Moderate----	Low to moderate

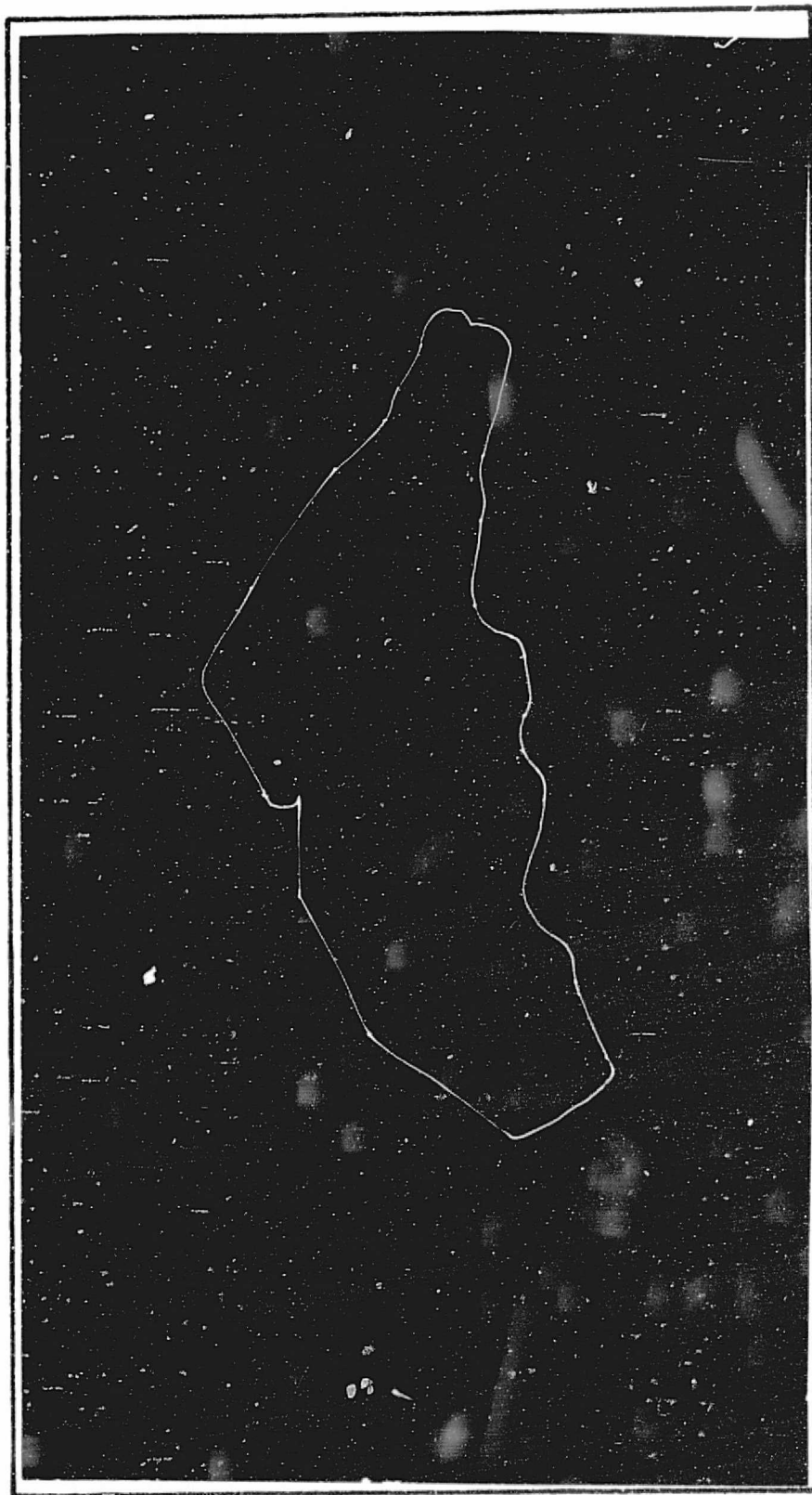
composite as described in Section 4. The color coding initially selected was the same as that used by the Earth Resources Observation Systems Data Center, i.e., Band 4 positive - yellow, Band 5 positive - magenta, and Band 7 positive - cyan. Figure 19 is an enlargement of the composite.

The analysis proceeded by transferring the area of the 9" X 9" diazo containing Bucklodge Branch onto color slide film. A 35mm camera with a slide copying attachment was used; this guarantees the color-fastness of the image to be analyzed. The slide was projected using the Mark I ECOSystems Universal Image Analyzer at a 1:24,000 scale. (41.7 X magnification).

The specific steps required to translate the colors to specific land use and cover classes were described in Section V and are summarized in the following:

Step 1: Location of Watershed: The ridge line of the Bucklodge Branch watershed was first demarked on the U.S.G.S. topographic map. This outline defined the area to be classified. The ECOSystems analyzer permits magnification of a projected image to predetermined scale. By adjusting the projection distance, the LANDSAT composite was enlarged to match the topo-map scale. The image is reflected off an overhead mirror and superimposed on the base map. An exact superposition is attained by adjusting the zoom lens until alignment is achieved between lakes, roads and/or other prominent unambiguous features in the scene. The watershed is thus bounded by the ridge line drawn on the map.

FIGURE 19: LANDSAT DIAZO COMPOSITE, BUCKLODGE BRANCH
WATERSHED, 6 October 1973



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A sheet of plain paper was placed over the topo map and the basin boundary traced on it. The map was no longer needed and was removed.

Step 2: Preliminary Land Use Classification: An initial assessment of how many separable themes exist within the basin was made by visual interpretation. "Themes" in this sense actually refers to a color in the LANDSAT composite. The interpreter determined how many separable colors could be identified by reference to a set of standard color chips as indicated in Section V.

Step 3: Analysis of Ground Truth: Aerial photographic ground truth was used to test classification accuracy of the LANDSAT imagery. It was prepared in color slide format and projected, in fashion similar to the satellite composite, to a scale of 1:24,000. The watershed ridge line was marked off. In this case, however, the interpreter identified individual land use classes rather than color. The resolution of the aerial photography was sufficient to permit separation to Levels 1-2 which is adequate detail for most modeling applications. Five classes were separated - forests, fields, agricultural (fallow), surface water, and urban areas.

Step 4: Correlation of Composite Color and Land Use Class: Examination of selected test areas in the LANDSAT image with corresponding points on the ground truth photograph yielded a correlation matrix of color and land use.

<u>COLOR</u>	<u>LAND USE</u>
Black	Surface water
Blue/White	Agricultural (Fallow)
Light Red	Fields
Dark Red	Forests
Red/Blue	Urban

Step 5: Analysis of Classification Results: The area of each class was measured with a calibrated grid overlay. The results are summarized in Table 6.

TABLE 6

SUMMARY OF CLASSIFICATION RESULTS

<u>CLASS</u>	<u>AREA, LANDSAT IMAGE (ha)</u>	<u>AREA, AERIAL PHOTO (ha)</u>	<u>RELATIVE ERROR</u>
Fields	1,479	1,510	-2%
Forests	767	738	+4%
Urban	10	9	+11%
Surface Water	7	8	-17%
Agricultural (Fallow)	87	85	+2%
TOTAL	2,350	2,350	2.7%

The classification results indicate a high overall accuracy. It was observed that large (greater than 10%) relative errors resulted only from classes with very small absolute areas (less than 1% of total watershed area). In the case of urban areas, for example, the 9 hectare total area was distributed over six separate sites, none larger than about three hectares. The total surface water area of 8 hec-

tares was divided among nine individual lakes. Figure 20 indicates that the relative error is a monotonically decreasing function of area of the class, as supported by theory. All points fall close to the theoretical line with the exception of agricultural (fallow) areas, which displayed an error less than that expected. This further indicates that, because of the radiometric characteristics of agriculture lands, October is a good time to "look" for these, i.e., their contrast with surrounding areas is particularly high. This demonstrates the value of multi-temporal imagery indicated in Section V.

6.2.2 Peak Event Modeling of Bucklodge Branch

A simulation for all of Bucklodge Branch was not attempted since the stream gage is not located at the outlet. Bucklodge Branch was modeled down to the gage point in order that the results could be verified. Figure 21 is a reproduction of the U.S.G.S. 1:24,000 scale topographic map of this section. The heavy lines delineate important subbasins. The data collected earlier indicated that there were no dramatic variations in soils, topography, flow length, or surface cover within any subbasin.

The model used approximates the natural basin subareas with rectangular strips possessing averaged surface and subsurface characteristics. For Bucklodge Branch, each subbasin was replaced by two strips representing the areas on either side of the main channel as shown in Figure 22. The area of each strip was set equal to that of the subarea it represents. Its length is assumed equal to the channel length. This fixes the width, which is indicative of the overland flow length.

FIGURE 20

LANDSAT vs. AERIAL INVENTORY ERROR - BUCKLODGE BRANCH

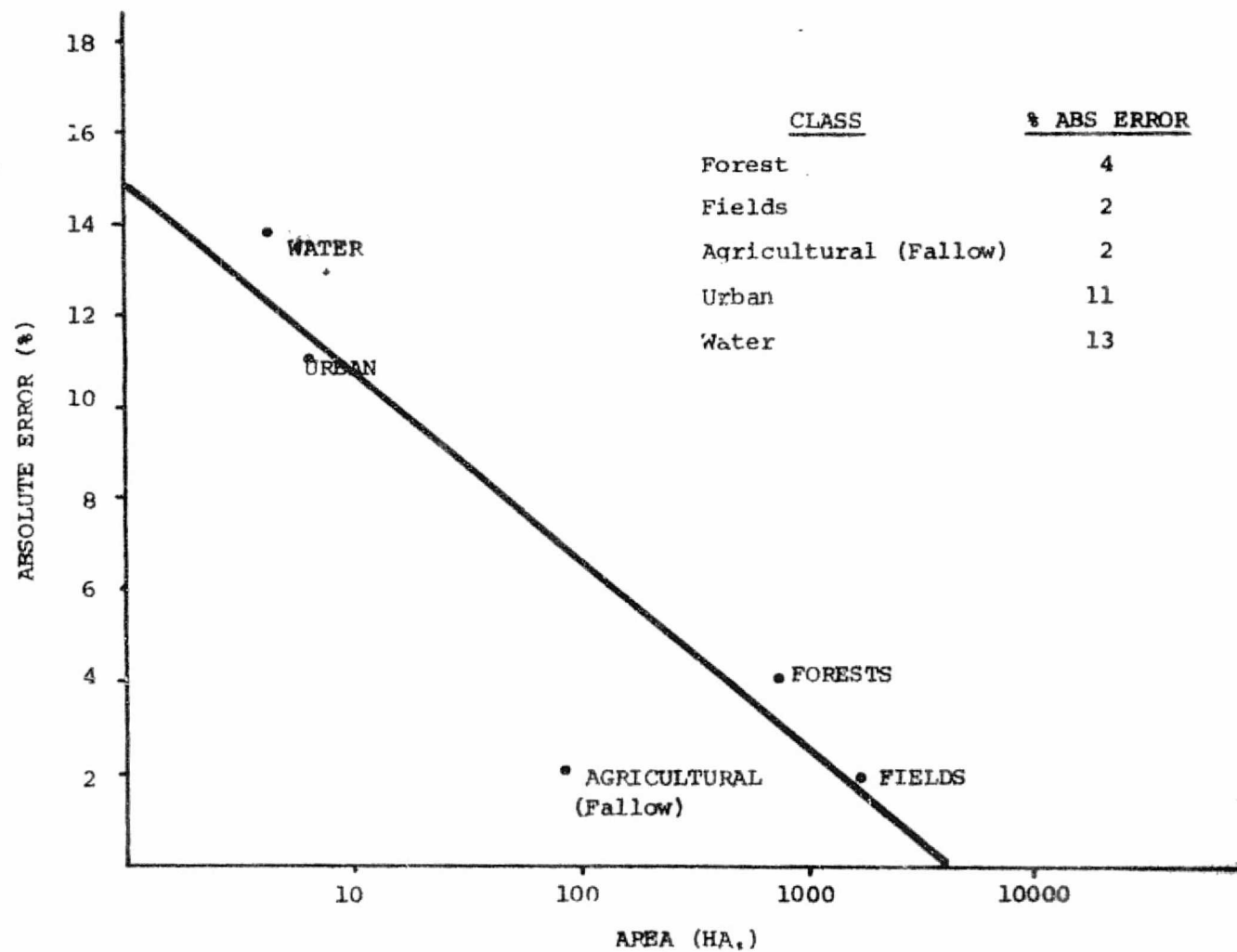


FIGURE 21 BUCKLODGE BRANCH
MAJOR SUBBASINS

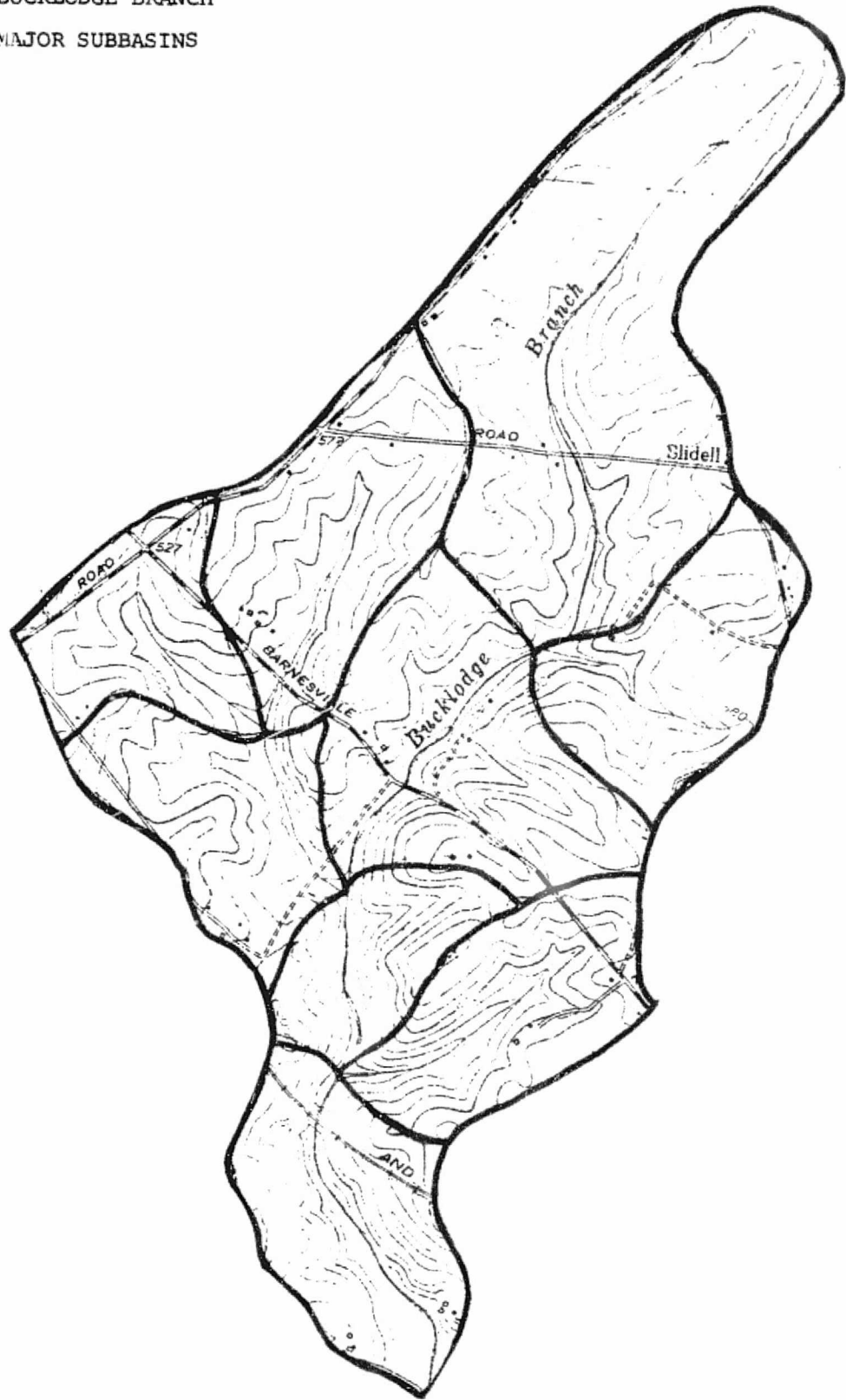
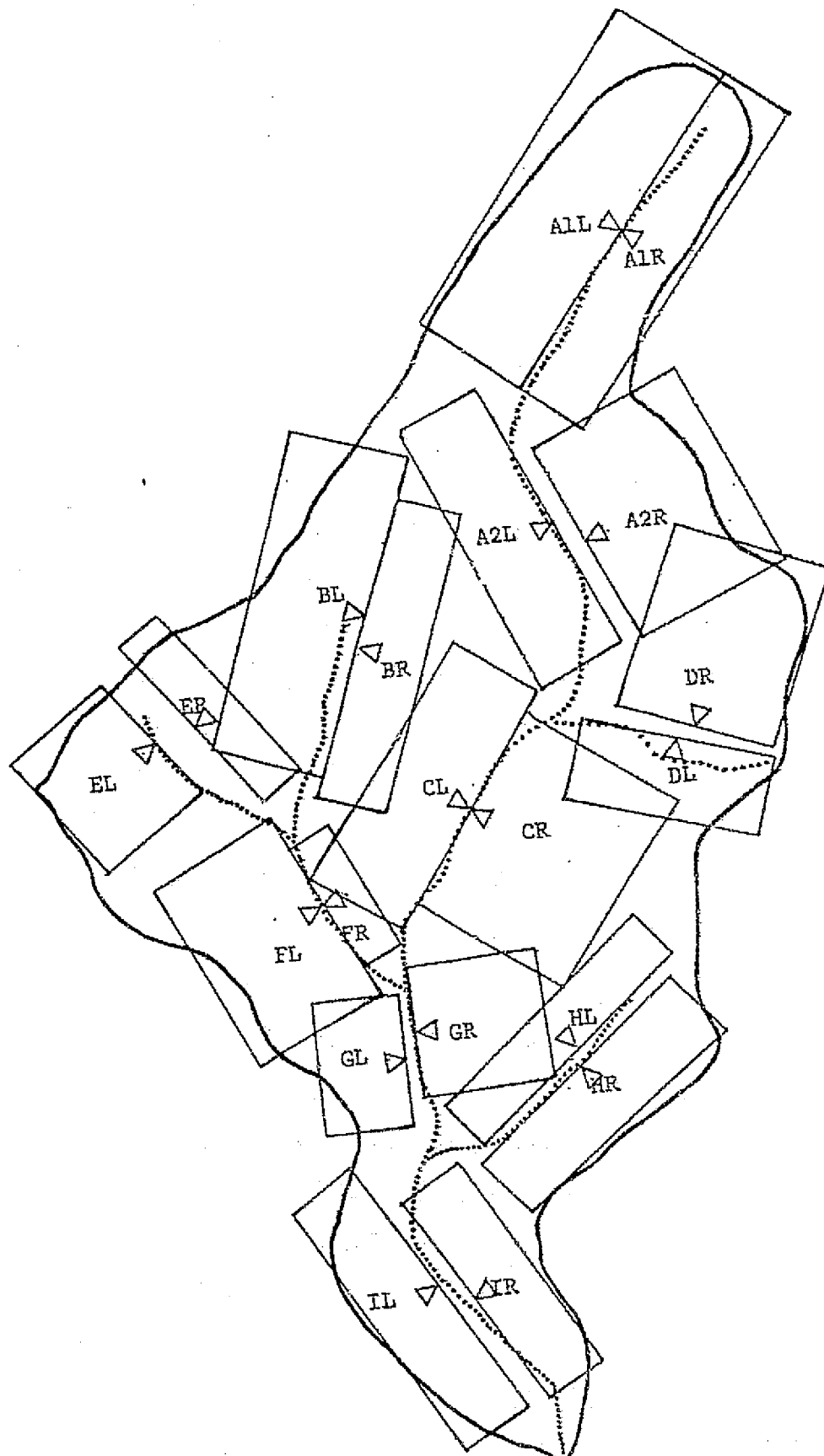


FIGURE 22

BUCKLODGE BRANCH - UNIT STRIPS



Slopes and soil parameters are averaged over the area of the strip. Table 7 summarizes the parameter assignment for each strip.

Figure 23 presents the hydrologic schematic for the surrogate watershed. The modelling process now requires that rainfall from a test event be input to each strip and the resultant runoffs routed down the channels. Characteristic rainfall test event were selected from among records obtained from the two rain gages in the watershed. The rain and resultant runoff stage readings are reproduced in Figure 24. Rainfall inputs applied to each strip were taken as a weighted average of the two raingages.

Model runs for the particular rain event selected showed that no overland flow was produced by thirteen of the twenty strips. Overland flow from the remaining seven were input to the routing module and the outflow hydrograph was derived. Preliminary runs indicate that overall basin response is heavily dependent upon the initial soil moisture condition assumed; a reasonable level of initial soil moisture was set, therefore, based on the analysis of rainfall for 14 days prior to the event. It should be noted that sensitivity to antecedent moisture is an important common characteristic of planning models: it may be a source of additional benefits from remote sensing of soil moisture in the future.

Results of the overland and routing runs are shown in Figure 25. The model exhibited a good approximation of actual discharge as computed from the gage records and rating curve. The results to date are encouraging. Even more important from the standpoint of modeling,

FIGURE 23

HYDROLOGIC SCHEMATIC - BUCKLODGE BRANCH

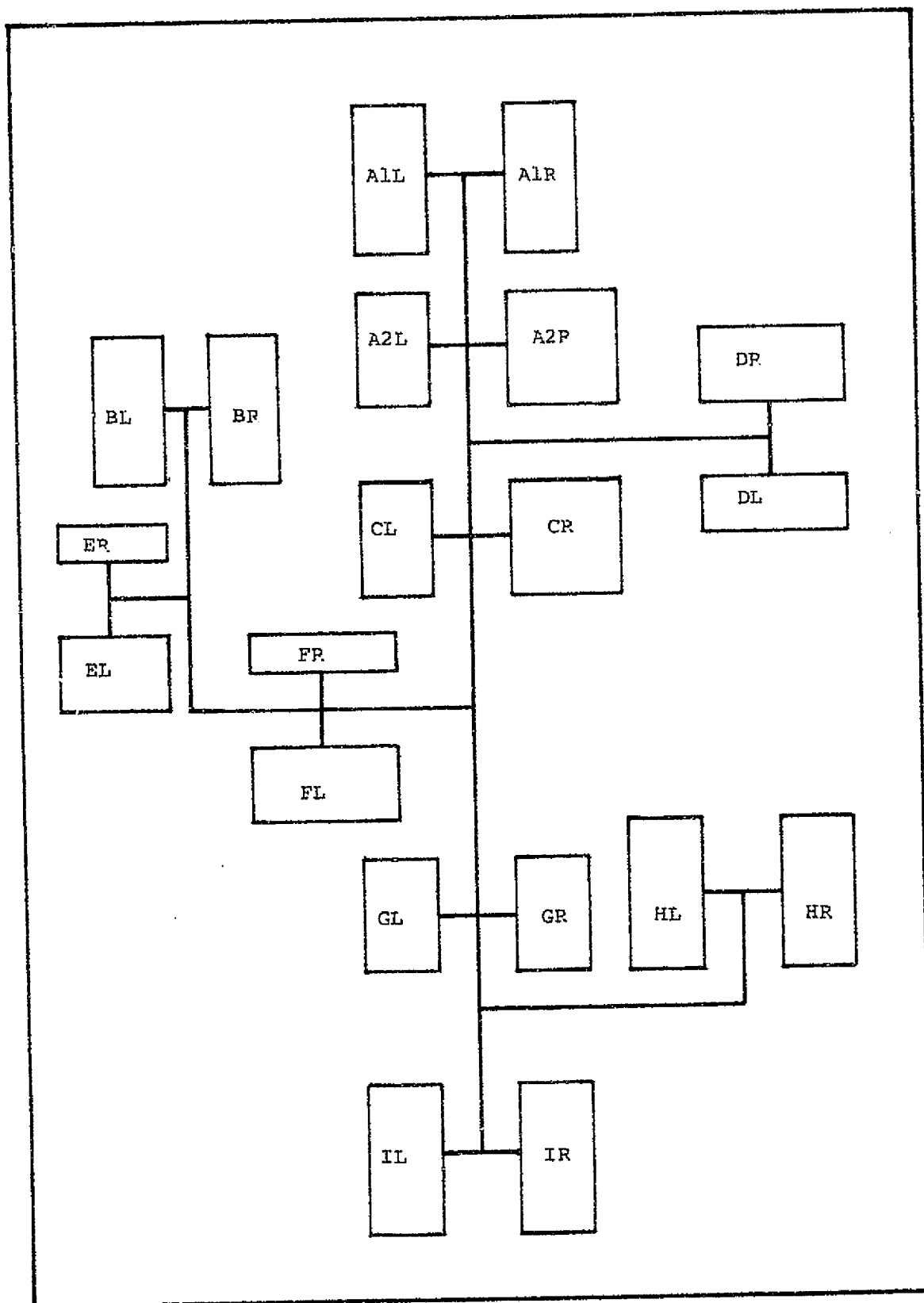
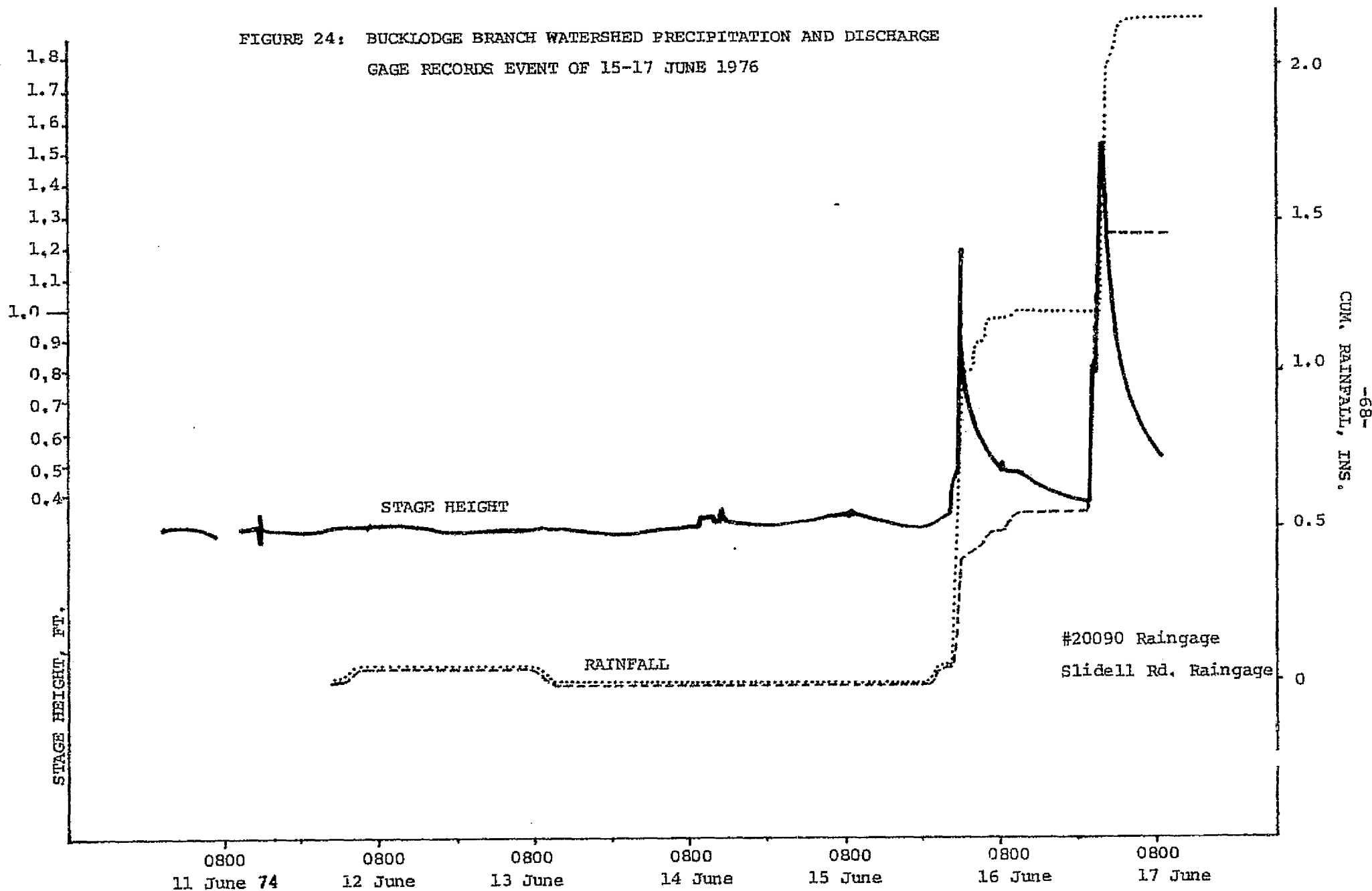


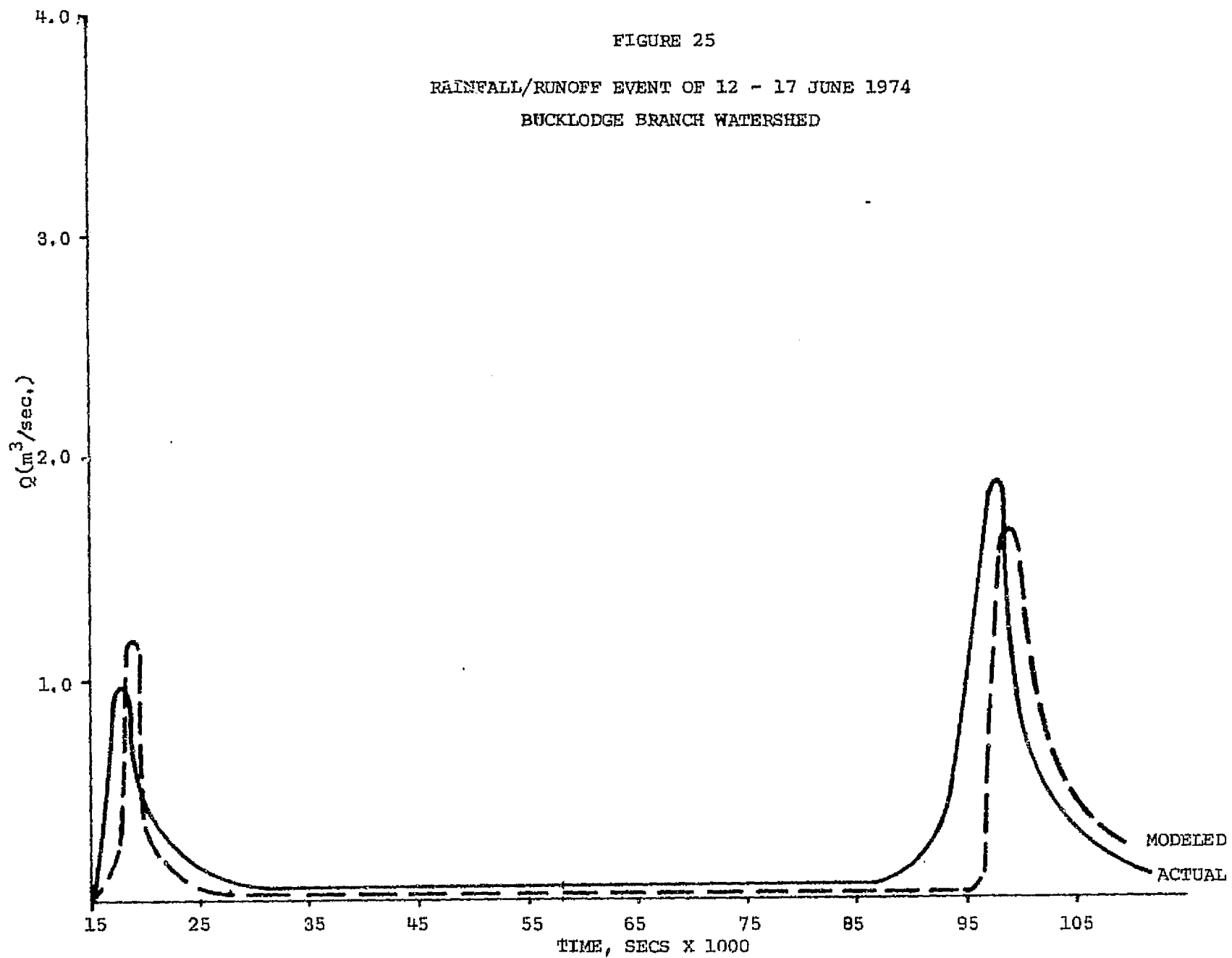
TABLE 7

BUCKLODGE - HYDROLOGIC DATA OF COMPONENT STRIPS

No.	STRIP	LENGTH (M)	WIDTH (M)	AREA (M ²)	SLOPE	MANNING'S N	MOISTURE CAPACITY (M)	PERC. (M/SEC)	FINAL INFILTRATION (M/SEC)
1	AIL	402.34	1626	6504.00	.040	.076	.038	.00000134	.000004445
2	AIR	271.27	1192	323353.84	.060	.076	.036	.00000119	.000004445
3	AR	463.29	1051	486917.79	.060	.044	.037	.00000105	.000004445
4	AZL	509.02	847	431292.40	.060	.031	.039	.000001129	.000004445
5	BL	505.97	852	431086.4	.070	.045	.063	.000001917	.000004445
6	BR	298.70	1207	360530.90	.080	.045	.036	.00000105	.000004445
7	CL	384.05	1045	401332.25	.080	.045	.035	.00000184	.000004445
8	CR	408.43	1237	505227.90	.080	.057	.038	.000001129	.000004445
9	DL	542.54	719	390086.26	.050	.056	.039	.00000127	.000004445
10	DR	304.80	793	241706.4	.060	.037	.060	.000001199	.000004445
11	EL	353.57	841	297661.70	.060	.055	.056	.000001129	.000004445
12	ER	323.09	518	167360.62	.060	.062	.066	.000001341	.000004445
13	FL	548.64	955	523951.2	.060	.044	.052	.000001199	.000004445
14	FR	201.70	443	89353.10	.090	.045	.030	.000000847	.000004445
15	GL	262.13	425	111405.25	.130	.084	.070	.0000014110	.000004445
16	GR	457.20	528	241401.60	.120	.081	.065	.00000134	.000004445
17	HL	286.51	986	282498.86	.110	.084	.066	.00000134	.000004445
18	HR	310.90	1100	341990.00	.070	.086	.048	.00000119	.000004445
19	IL	329.18	1230	404891.4	.110	.075	.066	.00000134	.000004445
20	IR	280.42	967	271166.14	.110	.097	.047	.00000134	.000004445

FIGURE 24: BUCKLODGE BRANCH WATERSHED PRECIPITATION AND DISCHARGE
GAGE RECORDS EVENT OF 15-17 JUNE 1976





however, is that the analysis techniques developed have been successfully related to actual hydrologic situations. This applicability extends beyond the model developed in this effort, and should prove valuable to a large class of modelers and users within the hydrologic community.

6.3 Implications of the Introduction of Remote Sensing Data into Hydrologic Planning Model

- 1, Satellite remote sensing can yield assessments of hydrologic land use sufficient for modeling purposes. The radiometric and multitemporal properties of the imagery can facilitate classification and provide new and additional information with respect to seasonal and developmental changes.
- 2, This information will be of value to a large section of hydrologic applications,
- 3, The assessment of soils and soil moisture conditions is presently difficult for modellers due to its temporal variability and the lack of records. Future inputs from remote sensing in this area would be most valuable.
- 4, The techniques derived and the demonstration made herein should function as a guide for the application of LANDSAT data by hydrologic modellers to their models on basins of concern to them.

VII. TECHNOLOGY TRANSFER TO THE USER COMMUNITY

The preceding analysis has indicated the applicability of remote sensing from LANDSAT to hydrology by confirming its adequacy as a source of surface cover information. The remaining problem was how best to introduce these results to users. Though hydrologists are generally familiar with conventional (aerial) remote sensing, the satellite data stream has not as yet seen wide use. This section will describe the problems involved in the technological transfer and the results achieved to date, and will present recommendations for future efforts.

7.1 Description of the User Community

Results from a previous NASA-GSFC/ECOSystems effort, synthesized following, characterized the hydrologic model users:

1. In the United States, agencies and organizations concerned with water resources number in excess of 6,000.
2. The principal contributor to research, development and implementation of water-resource models is the federal Government, with over 80% of the budget. Most of the federal effort is carried on by 11 federal agencies and their contractors.
3. In descending order of activity are state agencies (several hundreds), state water resources institutes (50), universities (70 principal), local governments (in excess of 3,000), and private contractors (approximately 3,000).

4. State water resource institutes and universities are primarily funded by the federal government. Most private contractors primarily support local Governments,
5. The eleven federal agencies which primarily "drive" hydrologic efforts are,

Department of Commerce - National Oceanographic &
Atmospheric Administration

Department of Agriculture

- a. Agricultural Research Service
- b. Soil Conservation Service
- c. Forest Service

Department of the Interior

- a. Geological Survey
- b. Bureau of Reclamation
- c. Fish and Wildlife Service
- d. Bonneville Power Administration

Environmental Protection Agency

Department of Defense - Army Corps of Engineers

Tennessee Valley Authority

6. The hydrologic community is diverse in its membership and in the models they use. There exists, therefore, no single focus at which satellite data analysis can be integrated into standard practice,

7. The diversity of users has recently been expanded with the emergence of several federal water resources planning programs which tend to move some of the activity away from federal groups and toward local and regional agencies. This further accentuates the need for using simple analysis procedures and hardware that can be employed within the constraints of local government budgets.

7.2 Impediments to Expanded Use of Remote Sensing in Hydrology and Suggestions for Overcoming Them

In addition to the diffuse make-up of the user community, two other problems are experienced in amplifying the use of LANDSAT data. There exists in any research activity a natural applications delay between invention and acceptance. New procedures must compete with everyday practice and must overcome an understandable inertia. In the case of LANDSAT data there exists a certain skepticism not dissimilar to the one encountered by any innovation. It is increased by the limitation of resources available to any one user, which makes him naturally hesitant to attempt new techniques without a certainty of their results. Such skepticism is healthy, however, and forces that the claims made for LANDSAT be thoroughly tested and made relevant to the user.

A recommended strategy for exposure of the new procedure, therefore, is not to represent LANDSAT as a panacea for all problems; rather, specific applications of interest to specific users should be "benchmarked." For this reason, this effort did engage in a specific benchmark test, as reported in Sections V and VI of this report. The test and the pro-

cedures developed and described herein can be repeated by any small or medium user on his own watershed, and the accuracy and cost of results thereby certified for his specific application.

7.3 Summary of User Contacts Made to Date

Efforts made during this study to foster the expanded use of remote sensing for hydrologic modeling encountered the impediments described above. Nevertheless, significant successes were also encountered with overseas users. Principal among these were:

- 1, A hydrologic modeling effort, based essentially upon the developments accomplished under NASA sponsorship, was contracted by the Region of Tuscany, Italy.

The model embraces a watershed of approximately 90,000 Hectares, with mixed urban, agricultural, forest, mountainous contents. The model must be able to:

- a) Predict runoff events in real time for matching supply against demand.
- b) Provide flood warning
- c) Provide accurate runoff predictions for unusual events (planning model) for the sizing of waterworks.
- d) Simulate the effect of changes in land use--reforestation, industrial parks, urban expansion---upon the watershed's hydrologic regime.

The effort additionally includes complete transfer of modeling and remote sensing technology to the customer.

This effort proved that the technique of planning models developed herein could be extended to general hydrologic modeling. The Tuscany model includes quarterly updates of the ground cover of the entire watershed from LANDSAT-derived information,

- 2, The specification of a facility for the analysis of LANDSAT data was contracted by the same customer. This includes visual and computerized data processing, employing their on-premise 370/135 computer, and using the LANDSAT data derived from the Telespazio receiving station located near Rome, Italy. The LANDSAT data are to be used for general land-use information as well as for hydrologic modeling.
- 3, An image-analysis device, of the type described previously, was acquired by the University of Naples, Italy, for the analysis of land use, water pollution and the inventory of selected crops.
- 4, A land-use map of high precision, including hydrologic properties, was contracted by the Region of Basilicata, Italy. The techniques employed will be those developed under this effort and reported herein.

The high interest of the foreign user community is attributed to the relatively small number of agencies working in hydrologic modeling and the concentration of these activities within regional governmental users.

The domestic situation differs in that the level of the technology transfer effort required is proportional to the number of users involved. On the domestic scene, initial contacts have been made to date with U.S.G.S., Water Resources Division; USDA, Agricultural Research Service, and the Maryland Department of State Planning. As previously discussed, cultivation of interest with these and other organizations will be greatly aided by concise benchmark tests,

APPENDIX A

STRIP HYDROGRAPH MODEL
FLOWCHART AND FORTRAN LISTING

FIGURE A1

STRIP MODEL WITH SOIL MOISTURE ACCOUNTING

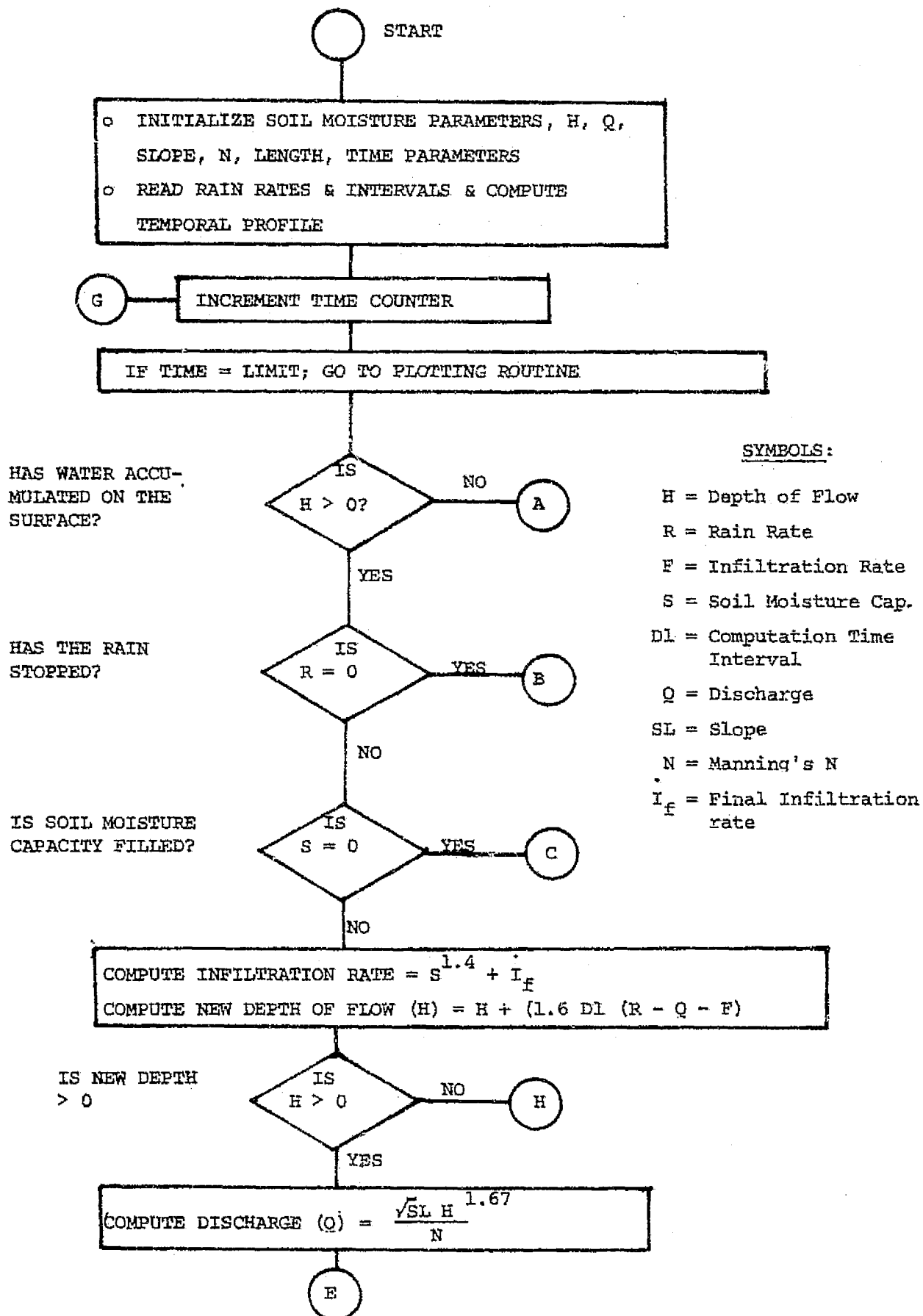


FIGURE A1 (cont'd)

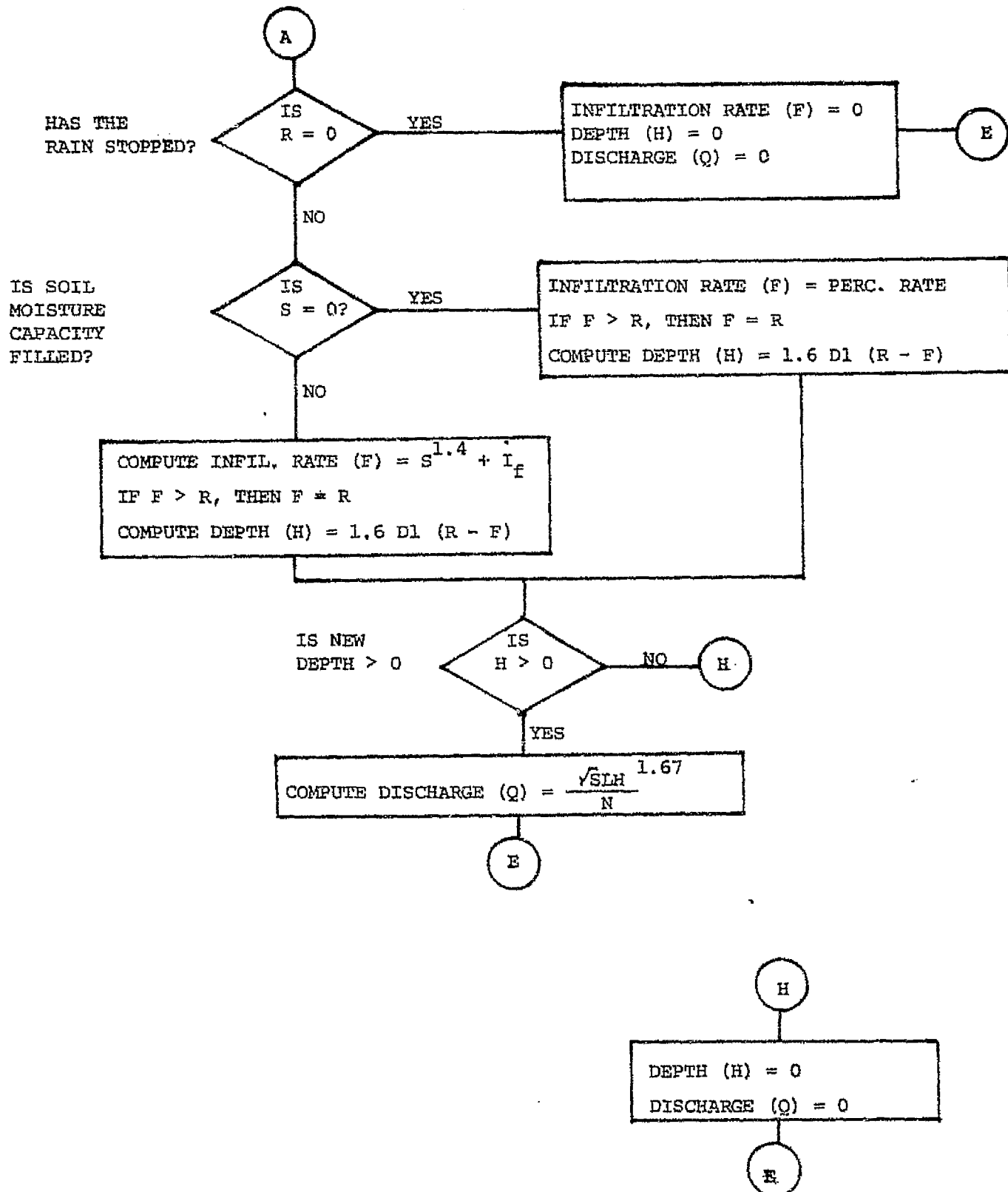


FIGURE A1 (cont'd)

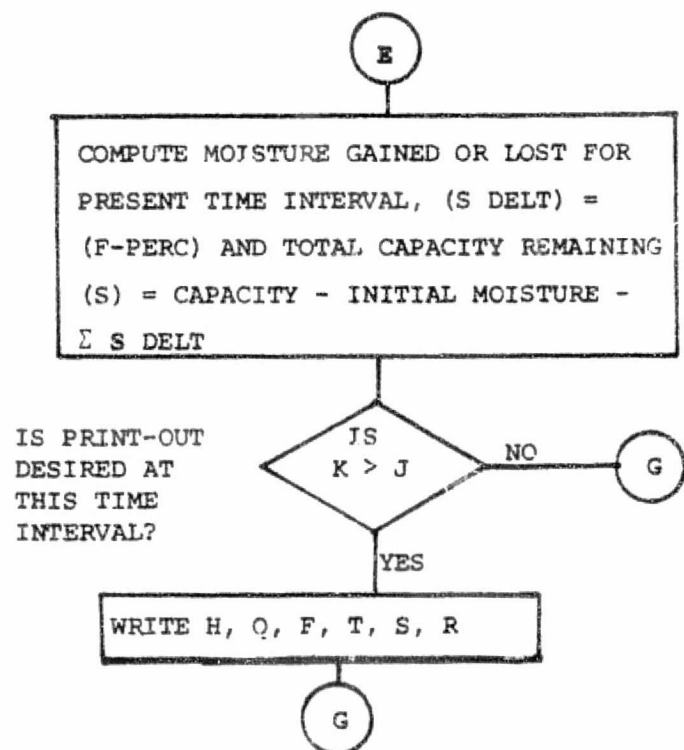
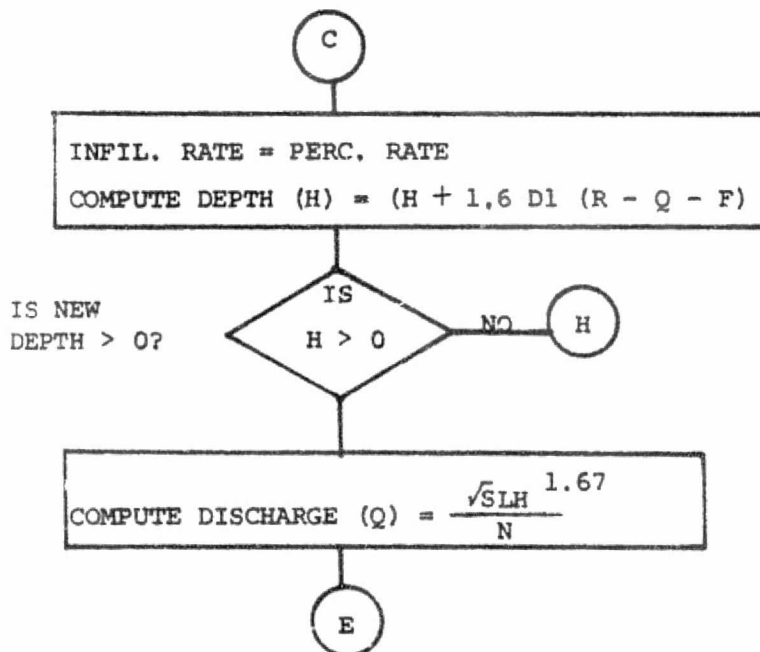
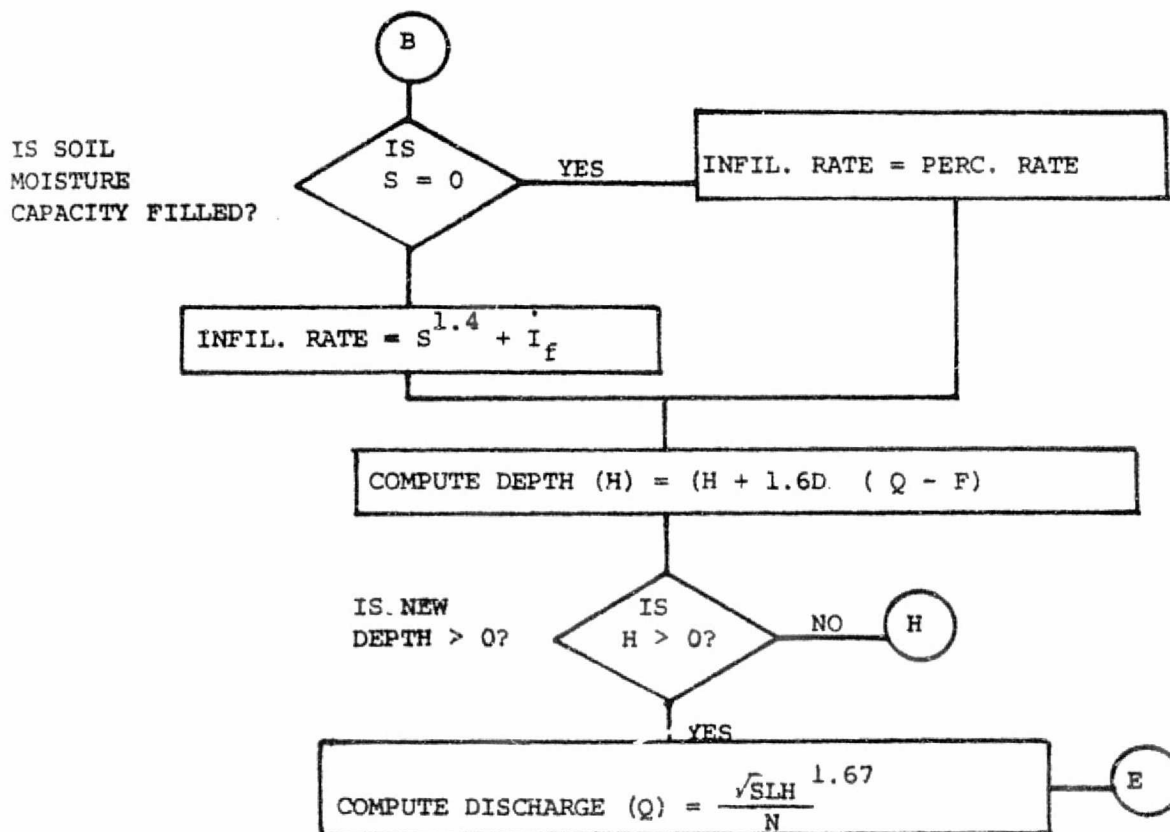


TABLE AI

FORTTRAN LISTING OF STRIP HYDROGRAPH MODEL

```

DIMENSION Q(500),R(500),S(500),F(500),XLN(100),U(25),V(25),H(25),CTR(15)
120 10 FORMAT ('ENTER LENGTH(M), SLOPE, MANNINGS N')
130 20 FORMAT (F7.2,F5.4)
140 30 FORMAT ('ENTER TIME STEP INCREMENT(SECS) AND NO. OF TIME STEPS')
150 39 FORMAT ('ENTER TIME SCALE STEP (SECS)')
160 40 FORMAT (F4.0,I3)
170 45 FORMAT ('ENTER TOTAL TIME LIMIT (SECS)')
180 46 FORMAT (I6)
190 94 FORMAT ('////,2X,' TIME(SECS)',4X,' DISCHARGE(M3/SEC*10 -4)',
200 95 FORMAT ('//,7X,10(F5.2,5X),F5.2)
210 205 FORMAT (5X,F9.2,5X,F15.10,5X,F15.10,5X,F15.10,5X,F15.10,5X,F15.10)
220 53 FORMAT ('ENTER NUMBER OF RAIN INCREMENTS')
230 60 FORMAT (I3)
240 70 FORMAT ('ENTER RAIN RATE(M/SEC) AND DURATION(SECS)')
250 80 FORMAT ('TOTAL RUN TIME MUST BE ACCOUNTED FOR')
260 70 FORMAT (F8.7,F5.0)
270 91 FORMAT (2F6.4,2F11.9)
280 92 FORMAT (5X,'0','3X','1',100A1)
290 99 FORMAT ('///,30X,'+ INDICATES INFILTRATION',//,30X,'+ INDICATES DISCHARGE',//,30X,'# INDICATES RAINFALL')
300 101 FORMAT ('ENTER SOIL MOISTURE CAPACITY(M); ANTECEDENT MOISTURE(M); PERC(M/SEC); FINAL INFIL.(M/SEC)')
310 141 FORMAT (3F9.7)
320 151 FORMAT ('////,6X,' TIME(SECS)',7X,' RAIN(M3/SEC)',7X,' INFIL.(M3/SEC)',11X,' H(M)',13X,' FLOW(M3/SEC)',10X,' CAP.(M)')
330 WRITE (100,10)
340 READ (105,20) XL,SL,EN
350 WRITE (100,30)
360 READ (105,40) D1,J
370 WRITE (100,45)
380 READ (105,46) N1
390 WRITE (100,50)
400 READ (105,60) J1
410 WRITE (100,101)
420 READ (105,91) CAP,API,PERC,F3
430 K(1)=0
440 WRITE (100,70)
450 WRITE (100,80)
460 DO 102 I=1,J1
470 READ (105,90) V(I),U(I)
480 J2=J1+1
490 DO 111 I=2,J2
500 111 M(I)=IDINT(U(I-1)/D1)+M(I-1)
510 DO 121 L=2,J2
520 L1 = M(L-1) + 1
530 L2 = M(L)
540 DO 121 K1=L1,L2
550 121 R(K1) = V(I-1)
560 N1 = M(J2)
570 N=IDINT(N1/D1)
580 F3=(SL**5/EN)
590 WRITE (100,151)
600 H=0.
610 SDELT=0.
620 K=0
630 S(1) = CAP-API
640 F3=F3*141732.
650 DO 321 I=1,N

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TABLE AI (cont'd)

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610 K=K+1
630 T = D1*I
640 IF (H .LE. 0.) GO TO 251
650 IF (R(I) .LE. 0.) GOTO 231
670 231 IF (S(I) .LE. 0.) GO TO 271
675 S(I) = S(I)*39.37
680 F(I) = ((S(I)**1.4+F3))
690 F(I) = F(I)/141732.
695 S(I) = S(I)/39.37
700 H=H+(1.6*D1*(R(I)-(Q(I-1)/XL)-F(I)))
710 IF (H .LE. 0.) GO TO 281
720 241 Q(I) = F5*.307*H**1.67
730 GO TO 291
740 251 IF (R(I) .LE. 0.) GO TO 255
750 IF (S(I) .LE. 0.) GO TO 257
760 S(I) =S(I)*39.37
770 F(I) = ((S(I)**1.4+F3))
775 S(I) = S(I)/39.37
780 F(I) = F(I)/141732.
790 IF (F(I) .GT. R(I)) F(I) = R(I)
800 H=1.6*D1*(R(I)-F(I))
810 253 IF (H .LE. 0.) GO TO 281
820 Q(I) = F5*.307*H**1.67
830 GO TO 291
840 255 F(I) =0.
850 H=0.
860 Q(I) =0.
870 GO TO 291
880 257 S(I) =0.
885 F(I) = PERC
890 IF (F(I) .GT. R(I)) F(I) = R(I)
900 H=1.6*D1*(R(I)-F(I))
910 GO TO 253
920 271 S(I) =0.
925 F(I) = PERC
930 H=H+(1.6*D1*(R(I)-(Q(I-1)/XL)-F(I)))
940 GO TO 253
950 281 H=0.
960 Q(I) =0.
970 291 SDELT = (F(I)-PERC)*D1
972 IF (SDELT .LT. (S(I)-CAP)) SDELT = S(I)-CAP
975 S(I+1)=S(I)-SDELT
976 IF (S(I+1) .LT. 0.) S(I+1)=0.
977 IF (S(I+1) .GT. CAP) S(I+1)=CAP
980 IF (K .LT. J) GO TO 321
990 WRITE (100,205) T,R(I),F(I),H,Q(I),S(I)
1010 K=0
1020 321 CONTINUE
1030 DATA STAR,BLANK,DOT,SLSH,PLUS,PND/'*',',',' ','+', '#'/
1040 37 FORMAT (2X,F5.0,3X,A1,100A1)
1050 WRITE (100,36)
1060 36 FORMAT (/////, 'ENTER MAXIMUM DISCHARGE - XX.XX')
1070 READ (105,38) Q
1080 38 FORMAT (F12.10)
1090 WRITE (100,39)
1100 READ (105,60) I2
1110 IX = I2/D1
1120 WRITE (100,99)
1130 WRITE (100,94)

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TABLE AI (cont'd)

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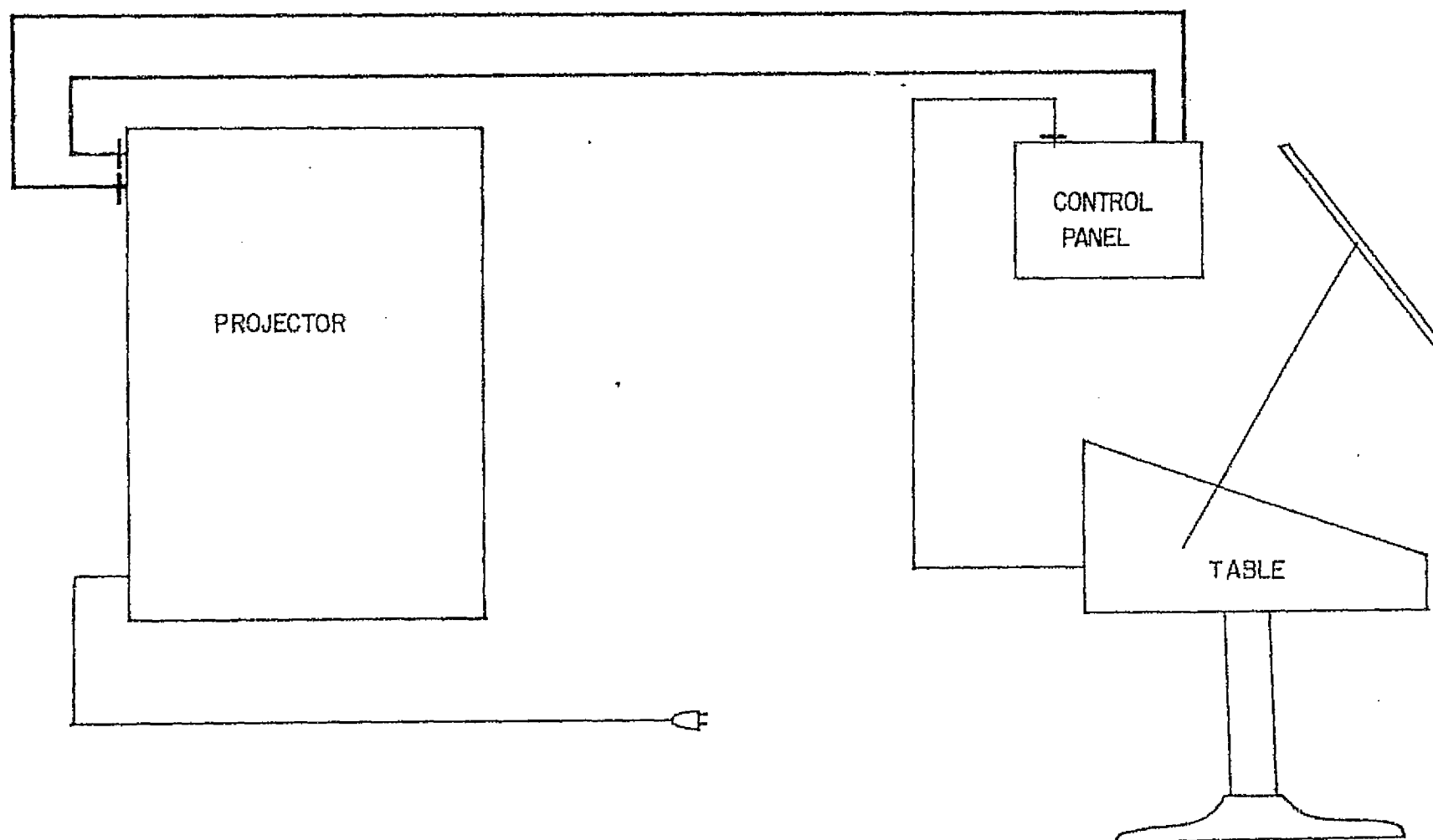
1140 H1=DM100.
1150 LM=0
1160 CTR(1) = 0.
1200 TIME = 0.
1210 D2=H1*10.
1220 DO 301 I=1,10
1230 301 CTR(I+1) = I*D2
1232 WRITE (100,95) (CTR(I),I=1,11)
1235 DO 300 J=1,100
1237 300 XLN(J) = DOT
1250 DO 309 I=10,100,10
1260 309 XLN(I) = SLSH
1270 WRITE (100,92) XLN
1280 DO 501 I=IX,N,IX
1290 TIME = TIME+12
1295 F(I) = F(I)*XL
1298 R(I) = R(I)*XL
1299 G=SLSH
1300 JA=IDINT((F(I)*10000)/H1+.5)
1301 IF (J6 .EQ. 0) G=PLUS
1304 J5 = IDINT((R(I)*10000.)/H1 + .5)
1305 IF (J5 .EQ. 0) G=PND
1308 J8 = IDINT((Q(I)*10000.)/H1 +.5)
1309 IF (J8 .EQ. 0) G=STAR
1310 LN=LN+1
1320 IF (LM .EQ. 5) GO TO 315
1330 DO 103 JK=1,100
1340 103 XLN(JK) = BLANK
1350 104 DO 105 JK=10,100,10
1360 105 XLN(JK) = SLSH
1363 IF (J6 .EQ. 0) GO TO 504
1365 XLN(J6) = PLUS
1380 504 IF (J5 .EQ. 0) GO TO 508
1385 XLN(J5) = PND
1386 508 IF (J8 .EQ. 0) GO TO 510
1387 XLN(J8) = STAR
1390 510 WRITE (100,37) TIME,G,XLN
1400 GO TO 501
1410 315 DO 109 JK=1,100
1420 109 XLN(JK) = DOT
1430 LM = 0
1440 GO TO 104
1450 501 CONTINUE
1460 STOP
1470 END

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-84-

APPENDIX B

UNIVERSAL IMAGE ANALYZER



MULTISPECTRAL IMAGE ANALYZER

SYSTEM FEATURES

The system is designed to perform scientific analysis of imagery: in particular from Landsat and Aircraft. It embodies in a single implementation the features found in existing image-analysis equipment, plus additional capabilities. The system is composed of an Image Projection and Control Unit which includes:

- 1) The Image Former
- 2) The Image Work Table Unit,

The system operates in two basic modes: a) the *Image Combination Mode*, b) the *Image Compositing Mode*.

In the *Image Combination Mode*, up to four black and white transparencies of the same scene are inserted into the Image Former. The four images are combined optically and projected simultaneously onto the Work Table as a single registered image. Various operations can be performed independently on each of the (up to four) images: selective filtering (color), flickering, fade-in-fade-out, light intensity dimming. The scale of the combined image can be magnified up to 100 times, allowing for example the superimposition of satellite imagery onto large-scale aerial photographs, topo maps and similar.

In the *Image Compositing Mode*, the black and white image representing each band is first developed onto a monochromatic image, which reproduces the original to a high fidelity of geometric registration. This can be done in any one of 9 color-hues. It is then possible to operate in two modes:

- a) Inserting each monocolor transparency (up to four), representing a different band, into the *Image Former*, superimposing and registering them, and projecting the combination onto the *Work Table*.
- b) Superimposing by simple means (external to the system) two or more single color images, representing different bands of the same scene, and constructing therefrom a single multicolored image. This image can then be inserted in any one of the four *Image Former* projectors and projected onto the *Work Table* for analysis.

Method b) allows the user to construct his own color composites, up to 220mm format, with the advantage that he can vary the density and color of each image to bring out the most desirable features. The economic advantage is the very low cost of compositing, which allows ample leeway for experimentation and optimization. The quality is fully comparable with EROS-type products.

A special case of working with composite images is the use of already-prepared color transparencies such as those purchasable from the EROS Data Center.

The basic advantages of the system are the following:

It can precision-expand the images up to 50:1, and up to 100:1 at lesser precision, thereby allowing superimposition of a wide range of imagery scales of the same area.

It provides the analyst with a clear and large image on a convenient, solid work table, without forcing him to look through lenses or optical devices, thereby providing the best match between man and machine.

It provides rapid, smooth, remote and flexible capability for registering images, changing colors, and applying various photointerpretation devices, allowing the analyst to use simultaneously all the tools available for maximal extraction of information from imagery.

It combines into a single device the features of the two basic systems currently available on the market, i.e.: 1) the transfer type systems, which project an image onto a flat surface, allowing superimposition; and 2) the color-additive systems, which combine various images of the same scene onto a single image. Existing transfer systems within the same price range do project single images, but do not combine multiple images; existing color-additive systems combine images, but have limited projection capability.

The system provides the added capability of reproducing high quality, density-controlled, precision-registered color images from the original black and white, at very low cost (approximately \$0.25 per copy). This capability represents an added degree of freedom in the radiometric domain.

The salient items of comparison between the systems are shown in Table B1.

An important consideration is the size of the image acceptable by the system. Landsat and most aerial images fall prevalently into the sizes of 70mm (54mm information size) and 9" X 9" or 225mm (185mm information size). In the case of Landsat, both sizes contain the same information: except that the Landsat pixel size is approximately 24 microns in the 70mm, 70 micron in the 220mm format. Since the eye's resolution is of order 70 microns, the 70mm imagery must be expanded 5-10X and the 220mm imagery 2-3X to reduce the contribution of the eye to within acceptable limits.

The expansion can be accomplished either by microscopy or by projection. Experience has shown that projection matches far better the human analyzer's psychophysiological preference. This is the first requirement for magnification. The second requirement stems from the

need to match the Landsat scale with commonly available ground truth scales. This is where the high magnification is most important.

Experience has shown that very seldom does one need to work with the entire Landsat frame (35,000 Km²). The overwhelming majority of applications deal with detailed studies of areas of hundreds, at most a few thousands of Km². The use of the entire Landsat frame is mostly limited to selecting the smaller area to be studied. Hence, there exists very little practical need, and significant added cost, to provide the capability to magnify 50 or 100X the large 220mm image. Instead, the Multispectral Analyzer System allows an equivalent capability to the user: namely to copy the 220mm image in essentially perfect rendition, and to cut therefrom the selected 70mm area (representing 3,000 km²) for projection.

TECHNICAL SPECIFICATIONS

IMAGE PROJECTION AND CONTROL UNIT

- o Handles up to four image transparencies of format 70mm, simultaneously.
- o Each of the four images can be spectrally filtered independently, via insertion of any combination of three quality color filters (Wratten #25 Red, #47 Blue, #8 Yellow, or equivalent) per image. Open gate position also provided. Filter insertion independently and remotely controlled on all four images (maximum of thirty two different color combinations).
- o Registration of all four images, or subsets thereof, by separate, remotely controlled three-degree of freedom adjustments: rotation, up-down (Elevation), right-left (Azimuth).

Caution: the capability to register the four images onto each other depends upon the precision of manufacture of the original imagery. For example, Landsat four-band imagery of the same scene is generally registered adequately. Landsat images of the same scene taken at different times (multitemporal) are in some cases not exactly registered one with the other. In this latter case, the equipment permits selective registration of any portion of the image under study.

- o Brightness of each of the four images vary independently by means of remotely controlled rheostat type dimmers. The brightness range is continuous from zero to maximum illumination. This permits the maximum separation of color unhampered by contrast/brightness effects.
- o Variable flicker capability remotely controlled with full interruption of light on all four images. Two flicker modes are provided; manual remote and automatic remote. In the automatic mode, the flicker continues automatically until turned

off by the operator: the flicker frequency is variable remotely by the operator. In the manual mode, the operator selects one or more of the images: flicker is provided by depressing a foot pedal. Typical useful flicker frequencies empirically determined are of order 2 cps.

- o Independent and remote focus on all four images.
- o Overall scale expansion on all four images, ratio up to 1:50 (1:1,000,000 scale imagery can be expanded to 1:20,000) in precision mode, up to 100:1 maximum. The scale range is set manually by translation of the image-forming equipment. The fine adjustment is provided by a remote-controlled, approximately 1:1.5, continuous scale expansion on all four images.
- o Manual fade-in fade-out control of the image by means of separate control which varies the illumination ratio between the imagery under study and the superimposed aerial photography or map.
- o Capability to photograph the image projected onto the work table. This is provided by means of a sturdy camera mount, easily attachable and detachable.
- o A vacuum system under on-off control by the operator can assist in holding the tracing paper or maps firmly onto the work table.

The control panel is of the "remove-and-relocate" type. It is movable to several positions (e.g., on either side, or one left one right of the operator), to best comply with the operator's preferences. Mechanical relocation of the control panel is accomplished by means of pre-arranged brackets and corresponding fasteners: electrical connections are relocated by means of multiple plugs.

- o Maximum dimension of image projected on work surface: approximately 60 x 50 centimeters.

- o Precision quality color-corrected lens train (Buhl variable focal length or equivalent) on each projecting system. Registration accuracy better than 20 microns at image center, no worse than 40 micron at edges (Referenced to original image).
- o The capability to evaluate image errors and distortions is provided by means of separately insertable optical reticle bearing calibration patterns.
- o Ruggedized metal construction, Operating ambient temperature: 14°C to 27°C . Storage temperature: -40°C to $+50^{\circ}\text{C}$. Shock and Vibration: Laboratory environment. Aero or autotransportable when packed in box supplied with equipment.
- o Power input: 110 volt A.C., 50-60Hz, angle phase approximately 2,000 watts.
- o Fuzing: Reseatable power breakers.
- o The equipment is designed for easy access for maintenance and repair without the need of specialized tools.

BIBLIOGRAPHY

Precipitation; Meteorology

- 1) Rainfall Frequency Atlas of the U.S., Dept. of Commerce, Weather Bureau, 1963.
- 2) Rainfall Intensity - Frequency Regime Report #29, Vol. 1-5, Eastern U.S., Dept. of Commerce, Weather Bureau, 1958.
- 3) Climatic Atlas of the U.S., Dept. of Commerce, E.S.S.A., Environmental Data Service, 1968.
- 4) Probable Maximum Precipitation, Susquehanna River Drainage Above Harrisburg, Pa., Hydrometeorological Report No. 41, Dept. of Commerce, Weather Bureau, June, 1965.
- 5) Probable Maximum and TVA Precipitation Over the Tennessee River Basin Above Chattanooga, Hydrometeorological Report No. 41, Dept. of Commerce, Weather Bureau, June, 1965.
- 6) Probable Maximum Precipitation, Northwest States, Hydrometeorological Report No. 43, Dept. of Commerce, Weather Bureau, November, 1966.
- 7) Probable Maximum Precipitation Over South Platte River, Colorado, and Minnesota River, Minnesota, Hydrometeorological Report No. 44, Dept. of Commerce, Weather Bureau, January, 1969.
- 8) Probable Maximum Precipitation, Mekong River Basin, Hydrometeorological Report No. 46, Dept. of Commerce, Weather Bureau, May, 1970.
- 9) Meteorology of Flood-Producing Storms in the Mississippi River Basin, Hydrometeorological Report No. 34, Dept. of Commerce, Weather Bureau, July, 1956.
- 10) Meteorology of Hydrologically Critical Storms in California, Hydrometeorological Report No. 37, Dept. of Commerce, Weather Bureau, December, 1962.

- 11) Meteorology of Flood-Producing Storms in the Ohio River Basin, Hydrometeorological Report No. 38, Dept. of Commerce, Weather Bureau, May, 1961.
- 12) "Accuracy of Precipitation Measurements for Hydrologic Modeling," L.W. Larson & E.L. Peak, presented at A.G.U. Spring Meeting, 1974.
- 13) "Methods of Estimating Areal Average Precipitation," A.F. Rainbird, Report No. 3, World Meteorological Organization, Reprinted in 1970.
- 14) "Measurement and Estimation of Evaporation and Evapotranspiration," Technical Note No. 83, World Meteorological Organization, Reprinted in 1971.
- 15) Storm Rainfall in the U.S.; Depth - Area - Duration Data, U.S. Army Corps of Engineers, July 1973.
- 16) Climatological Data, and Local Climatological Data for Washington, D.C.; Maryland; & Delaware, Aug. 1972 to present, U.S. Dept. of Commerce, N.O.A.A.
- 17) Meteorological Drought, Research Paper No. 45, U.S. Dept. of Commerce Weather Bureau, 1965.

Soils

- 1) Soil Survey Manual, Soil Conservation Manual, 1951.
- 2) Soil Survey, Dorchester County, Md., U.S.D.A. and Maryland Agricultural Experiment Station, 1963.
- 3) Soil Survey, Carroll County, Md., U.S.D.A. and Maryland Agricultural Experiment Station, 1969.
- 4) Soil Survey, Prince George's County, Md., U.S.D.A. (S.C.S.) and Maryland Agricultural Experiment Station, 1967.
- 5) Soil Survey, Marshall County, Miss. U.S.D.A. (S.C.S.) and Mississippi Agricultural Experiment Station, 1972.

- 6) Soil Survey, Caddo County, Okla., U.S.D.A. (S.C.S.) and Oklahoma Agricultural Experiment Station, 1973.
- 7) Soil Survey, Webster County, Neb. U.S.D.A. (S.C.S.) and University of Nebraska, Conservation and Survey Division, 1974.
- 8) Soil Survey, Grant County, Wisc. U.S.D.A. (S.C.S.); Wisconsin Geological and Natural History Survey; Wisconsin Agricultural Experiment Station, 1961.
- 9) Soil Survey, McLannan County, Texas U.S.D.A. (S.C.S.) and Texas Agricultural Experiment Station, 1942.
- 10) Aerial-Photo Interpretation in Classifying and Mapping Soils, Agriculture Handbook 294, Soil Conservation Service, U.S.D.A., 1966.
- 11) World Soils, E.M. Bridges (University Press: Cambridge, 1970).
- 12) S.C.S. Soil Group Classes, S.C.S. Hydrology Handbook.

Models & Modeling

- 1) Digital Simulation in Hydrology: Stanford Watershed Model IV, N.H. Crawford & R.K. Linsley, Dept. of Civil Engineering, Stanford University, July 1966.
- 2) Numerical Simulation of Watershed Hydrology (Texas Watershed Model), OWRR Technical Report HYD 14-7001.
- 3) Network Analysis of Runoff Computation (Chicago Hydrograph Model), C.J. Keifer, J.P. Harrison, T.O. Hixson, 1970.
- 4) "A Uniform Technique for Determining Flood Flow Frequencies Water Resources Council," 1967.
- 5) "Development of a Mathematical Model for the Simulation of Flat-Land Watershed Hydraulics," D.W. Deboer & H.P. Johnson, Iowa State University, November 1, 1969.

- 6) "Evaluation of a Deterministic Model for Predicting Water Yields from Small Agricultural Watersheds in Virginia," V.O. Shanholtz, J.B. Burford, & J.H. Lillard, Dept. of Agric. Engineering Research Division, Virginia Polytechnic Institute and State University, August, 1972.
- 7) "Investigation of a Linear Model to Describe Hydrologic Phenomenon of Drainage Basins," F.A. Schmer, Technical Report 19, Water Resources Institute, Texas A&M University, December, 1969.
- 8) National Weather Service River Forecast System Forecast Procedures, (HYDRO-14), Staff, Hydrologic Research Laboratory, December, 1972.
- 9) Computer Program for Project Formulation - Hydrology, Technical Release No. 20, U.S.D.A., Soil Conservation Service, May 1965.
- 10) A Generalized Streamflow Simulation System, U.S.D.C. (National Weather Service) and California Dept. of Water Resources, March, 1973.
- 11) A Distributed Linear Representation of Surface Runoff, W.O. Maddaus and P.S. Eagleson, MIT, Dept. of Civil Engineering, June 1969.
- 12) Water Balance Program, U.S. Forest Service, July, 1968.
- 13) "Continuous Hydrograph Synthesis With An API-Type Hydrologic Model," W.T. Sittner, C.F. Schauss, J.C. Monro, Water Resources Research, Oct, 1969 P 1007-1021.
- 14) Analog Computer Simulation of the Runoff Characteristics of an Urban Watershed, V.V. Dhruva Narayana, J.P. Riley, E.K. Israelson; Utah State University, Jan. 1969.
- 15) Mathematical Simulation of Hydrologic Events on Ungaged Watersheds, L.F. Huggins & E.J. Monke, Purdue Univ. Water Resources Research Center, March 1970.
- 16) Calibration of U.S. Geological Survey Rainfall/Runoff Model for Peak Flow Synthesis - Natural Basins, U.S.G.S., October 1973.

- 17) USDAHL-74 Revised Model of Watershed Hydrology, H.N. Holtan, G.J. Stiltner, W.H. Henson, N.C. Copey. U.S.D.S., July, 1974.
- 18) COSSARR Model - Streamflow Synthesis and Reservoir Regulation, U.S. Army Engineer Division, North Pacific, Portland, Oregon, January, 1972.
- 19) Runoff Evaluation and Streamflow Simulation by Computer, U.S. Army Engineer Division, North Pacific, Portland, Oregon, May, 1971.
- 20) Generalization of Streamflow Characteristics from Drainage Basin Characteristics, D.M. Thomas & M.A. Benson, U.S.G.S., 1969
- 21) "Soil Surface Characteristics and Rainfall-Runoff-Moisture Relationships on Coastal Plain Soils," Ronald E. Hermanson, Water Resources Research Institute, Auburn University, 1970.
- 22) "Stochastic Analysis of Hydrologic Systems," Ven Te Chow, Dept. of Civil Engineering, University of Illinois at Urbana-Champaign, Research Report No. 26, December, 1969.
- 23) "The Use of Analog and Digital Computers in Hydrology," Proceedings of the Tucson Symposium, International Hydrological Decade, UNESCO, 1969.

Floods & Flooding

- 1) Magnitude and Frequency of Floods in the U.S., U.S.G.S., 1964.

Part 2-A - South Atlantic Slope Basins, James River to Savannah River;

Part 2-B - South Atlantic Slope and Eastern Gulf of Mexico Basins, Ogeechee River to Pearl River;

Part 3-A - Ohio River Basin Except Cumberland and Tennessee River Basins;

Part 3-B - Cumberland and Tennessee River Basins;

Part 5 - Hudson Bay and Upper Mississippi River Basins;

- Part 6-A - Missouri River Basin above Sioux City, Iowa;
- Part 6-B - Missouri River Basin below Sioux City, Iowa;
- Part 7 - Lower Mississippi River Basin;
- Part 8 - Western Gulf of Mexico Basins;
- Part 9 - Colorado River Basin;
- Part 10 - The Great Basin;
- Part 11 - Pacific Slope Basins in California - (Vol. 1 - Coastal Basins South of the Klamath River Basin & Central Valley Drainage from the West);
- Part 11 - Pacific Slope Basins in California - (Vol. 2 - Klamath and Smith River Basins and Central Valley Drainage from the East);
- Part 13 - Snake River Basin

- 2) "Estimation of 100 Year Flood Magnitudes at Ungaged Sites," C.H. Hardison, U.S.G.S., Water Resources Div., 1973.
- 3) Meteorology of Hypothetical Flood Sequences in the Mississippi River Basin, Hydrometeorological Report No. 35, Dept. of Commerce, Weather Bureau, December 1959.
- 4) Meteorological Criteria For Extreme Floods For Four Basins in the Tennessee and Cumberland River Watersheds, Hydrometeorological Report No. 47, Dept. of Commerce, National Oceanic and Atmospheric Administration, July 1971.
- 5) Arizona Floods of September 5 and 6, 1970, Natural Disaster Survey Report 70-2, Dept. of Commerce, National Oceanic and Atmospheric Administration, July 1971.
- 6) Black Hills Flood of June 9, 1972, Natural Disaster Survey Report 72-1, Dept. of Commerce, National Oceanic and Atmospheric Administration, August 1972.

- 7) The National River and Flood Forecast and Warning Service - (A Plan for Improving), Dept. of Commerce, Weather Bureau, December, 1969.
- 8) "Flood-Hydrographs Analyses and Computations," Engineering & Design, Corps of Engineers, U.S. Army, 31 Aug. 59.
- 9) "Generalized Skew Coefficients of Annual Floods in the U.S. and Their Application," C.H. Hardison, U.S.G.S., 1974.
- 10) "Implicit Dynamic Routing of Floods and Surges in the Lower Mississippi," D.L. Fread, for presentation at A.G.U. Spring Meeting, 1974.
- 11) "Estimation of Maximum Floods," World Meteorological Organization, Reprinted in 1972.
- 12) "Forecasting of Heavy Rains and Floods," World Meteorological Organization, 1970.
- 13) "Floods and Their Computation," Proceedings of the Leningrad Symposium, Volume 1, August, 1967 - UNESCO-WMO.

Hydrology & Hydrologic Processes

- 1) Water Atlas of the United States, Water Information Center, 1973.
- 2) The Water Encyclopedia, D.K. Todd, Water Information Center, 1970.
- 3) The Nation's Water Resources, U.S. Water Resources Council, 1968.
- 4) Water Publications of State Agencies, Water Information Center, 1972.
- 5) Representative and Experimental Research Basins in the United States, International Hydrological Decade, 1969.
- 6) Water Resource Development in Maryland, U.S. Army Corps of Engineers, North Atlantic Division, 1973.

- 7) Baltimore County Hydraulic Design Manual, Baltimore Co., Md., 1968.
- 8) Anne Arundel County Hydraulic Design Manual, Anne Arundel Co., Maryland.
- 9) The Missouri River Basin Comprehensive Framework Study, Missouri Basin Inter-Agency Committee, Vol. 1-7, December 1971.
- 10) "River Runoff Theory and Analysis," D.L. Sokolovskii, Environmental Science Services Administration, Dept. of Commerce, 1971.
- 11) "Suggested Criteria for Hydrologic Design of Storm-Drainage Facilities in the San Francisco Bay Region California," Dept. of the Interior, Geological Survey, Water Resources Division, November 24, 1971.
- 12) National Atlas of the United States of America, Dept. of the Interior, Geological Survey, 1970.
- 13) "A Concept for Infiltration Estimates in Watershed Engineering," H. Holtan, Agricultural Research Service, U.S.D.A., 1961.
- 14) "Derivation of an Equation of Infiltration," H.J. Morel-Seytoux and J. Khanji, Water Resources Research, August 1974.
- 15) "Systematic Treatment of Infiltration With Applications," H.J. Morel-Seytoux, Environmental Resources Center, Colorado State University Report No. 50, June 1973.
- 16) Annotated Bibliography on Hydrology and Sedimentation 1966-1968, U.S. and Canada, Joint Bulletin No. 10, Water Resources Council for Soil Conservation Service U.S.D.A.
- 17) Handbook of Applied Hydrology, Ven Te Chow McGraw-Hill Book Co., 1964.
- 18) Open Channel Hydrology, Ven Te Chow, McGraw-Hill Book Co., 1959.

- 19) Introduction to Hydrology, Viesmann, Harbaur & Knapp, Intext Educational Publishers, 1972.
- 20) "Time of Concentration for Overland Flow," W.S. Kerby, Civil Engineering, March 1959, p. 60

Watershed Sample

- 1) "Representative and Experimental Basins," C. Toebes and V. Ouryvaev, eds., International Hydrological Decade, UNESCO, 1970.
- 2) "Hydrologic Data for Experimental Agricultural Watersheds in the U.S., 1956 - 1967, Misc. Publications No. 1262, 1226, 1216, 1194, 1164, 1070, 904, & 945, Agricultural Research Service, U.S.D.A.
- 3) Monthly Precipitation and Runoff for Small Agricultural Watersheds in the U.S., U.S., U.S.D.A. Agricultural Research Service, June 1957.
- 4) Selected Runoff Events for Small Agricultural Watersheds in the United States, U.S.D.A., Agricultural Research Service, January 1960.
- 5) Annual Maximum Flows from Small Agricultural Watersheds in the United States, U.S.D.A., Agricultural Research Service, June 1958

Miscellaneous

- 1) Storm Water Management - A Comprehensive Study of the Muddy Branch and Seneca Creek Watershed, Cornell, Howland, Hayes, and Merryfield, Clair A. Hill & Associates, April, 1975
- 2) User Requirements and User Acceptance of Current and Next Generation Satellite Mission and Sensor Complement, Oriented Toward the Monitoring of Water Resources; Ecosystems International, Inc.; Castruccio, Loats, Fowler and Robinson, NAS5-20567, December, 1975.